Naval Research Laboratory

Stennis Space Center, MS 39529-5004

PCTides Validation Test Report

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March 10, 2006

REPORT DOCUMENTATION PAGE

1. REPORT DATE *(DD-MM-YYYY)* 10-03-2006	2. REPORT TYPE Memorandum Report	3. DATES COVERED *(From - To)*

4. TITLE AND SUBTITLE

PCTides Validation Test Report

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
0602435N

6. AUTHOR(S)

Pamela Posey, Ruth Preller, and Gretchen Dawson

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER
73-6646-06

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Naval Research Laboratory
Oceanography Division
Stennis Space Center, MS 39529-5004

8. PERFORMING ORGANIZATION REPORT NUMBER

NRL/MR/7320--06-8910

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Office of Naval Research
One Liberty Center
875 North Randolph Street
Arlington, VA 22217-1995

10. SPONSOR / MONITOR'S ACRONYM(S)

ONR

11. SPONSOR / MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES

14. ABSTRACT

The Naval Research Laboratory (NRL) has built a globally relocatable tide-surge forecast system. Currently, this system runs on a UNIX platform, but was originally designed for PC-based use, and, as such, is referred to as "PCTides." The system is composed of a two-dimensional barotropic ocean model, which is driven by tidal forcing and/or surface wind and pressure forcing. PCTides is applied to the user's area of interest to provide a hindcast or forecast of tidal amplitude, phase and two-dimensional barotropic ocean currents. The PCTides system uses the solutions from a global tide model Finite Element Solutions 99 (FES99) to provide global boundary conditions. The system also contains a 2-min global bathymetry database (the NRL DBDB2 database) to define the model's geometry and bathymetry. Wind forcing for PCTides comes from a number of sources. If the user has access, the Navy's Global Atmospheric Prediction System (NOGAPS), or the Coupled Ocean & Atmospheric Mesocale Prediction system (COAMPS) may be used. Based on this model, hurricane forcing can be generated that can provide surface pressure and winds to drive the two-dimensional barotropic ocean model and generate a storm surge. One major advantage of PCTides is that the model has the ability to be rapidly relocated to areas of interest. The tidal heights can be generated at a user-specified latitude/longitude position and, therefore, is not dependent on a tidal "look up" table or preexisting database of preselected locations.

15. SUBJECT TERMS

PCTides	Algorithm
Barotropic	OAML

16. SECURITY CLASSIFICATION OF:

a. REPORT	b. ABSTRACT	c. THIS PAGE
Unclassified	Unclassified	Unclassified

17. LIMITATION OF ABSTRACT

UL

18. NUMBER OF PAGES

48

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Executive Summary

The Naval Research Laboratory (NRL) has built a globally relocatable tide-surge forecast system. Currently this system runs on a UNIX platform but was originally designed for PC-based use and as such is referred to as "PCTides". The system is composed of a two-dimensional barotropic ocean model driven by tidal forcing and/or surface wind and pressure forcing. PCTides is applied to the user's area of interest to provide a hindcast or forecast of tidal amplitude, phase and 2-dimensional barotropic ocean currents. The PCTides system uses the solutions from a global tide model (FES99) (Lefevre et al., 2000) to provide global boundary conditions. The system also contains a 2-minute global bathymetry database, the NRL DBDB2 database, to define the model's geometry and bathymetry. PCTides may be run in a mode loosely constraining the solutions to a subset of more than 4000 tidal observations stations from the International Hydrographic Observations (IHO) database (Anonymous, 1988). Wind forcing for PCTides comes from a number of sources. If the user has access, the Navy's Global Atmospheric Prediction System (NOGAPS) (Hogan and Rosmond, 1991) or the Coupled Ocean and Atmospheric Mesoscale Prediction System (COAMPS™) (Hodur, 1997) may be used. The PCTides system also includes a "hurricane model" developed by Holland (1980). Based on this model, hurricane forcing can be generated that can provide surface pressure and winds to drive the 2-dimenional barotropic ocean model and generate storm surge. One major advantage of PCTides is that the model has the ability to be rapidly relocated to areas of interest. The tidal heights can be generated at a user-specifed latitude/longitude position and therefore is not dependent on a tidal "look up" table or pre-existing database of pre-selected locations.

This report documents the validation of PCTides in different geographic areas demonstrated by NRL and outside experts and agencies.

PCTides Validation Test Report

Introduction

The U.S. Naval Research Laboratory has developed a globally relocatable tide/surge forecast system. PCTides runs on Windows 2000 and XP machines in a DOS mode and both on UNIX and LINUX platforms. PCTides is also currently run on the High Performance Computers (HPC machines) and is the tidal prediction component in the PC-based Distributed Integrated Ocean Prediction System (Allard et al., 2005).

The U.S. Navy has a requirement to produce global tide prediction forecasts (CINC Ocean 91-14, "Tidal Predictions to Support Navy Operations"). The PCTides system was developed to fill a void in the Navy's global tide forecasting capability. Tidal forecasts available to the Navy are presently limited to locations where there are coastal tidal water level observation stations. As such, the Navy has been limited to forecasts at specific locations with limited capability to estimate tidal amplitude between stations. In addition, these forecasts could not include the effects of winds (surge), which could play a substantial role in water level prediction. PCTides is a globally relocatable tide forecasting system designed to predict tides at any location. In addition, it can include wind/pressure forcing in its predictions. PCTides was specifically designed for short-term (weekly) forecasts of tidal amplitudes, however longer forecasts can be made if necessary.

The PCTides system has been accepted into the Ocean and Atmospheric Master Environmental Library (OAML). A PC version of the system was submitted to OAML in 2002. It was determined after this delivery, that along with the PC version of the system, a UNIX format should also be available. Therefore, over the next year, NRL revised the PCTides system into both a UNIX and a PC format that were identical except for a GUI associated with the PC version. In addition, a number of upgrades were included into the PCTides system making a substantial improvement from the first version. As such, the original version of PCTides (PCTides 1.0) was withdrawn from OAML delivery and PCTides 2.0 was delivered in its place in October 2003.

Prior to the delivery of PCTides 1.0, the system was evaluated by NRL, the developer, and by the Naval European Meteorology and Oceanography Command (NEMOC – Rota, Spain) as a beta-test center. The NEMOC evaluators provided a letter of assessment of the model (Appendix A). In addition, a tidal expert from the United Kingdom, Dr. Roger Proctor of the Proudman Oceanographic Laboratory (POL), visited NRL as part of the ONR London Visiting Scientist Program, and tested the PCTides system in and around the UK coastal waters. The PCTides system was installed and produced results comparable to the UK tidal models within a short time (week) demonstrating the rapidly relocatable character of the system. Dr. Proctor compared these results to observations as well as to existing POL tidal prediction models and provided a statement on the fidelity of PCTides (Appendix B).

PCTides 1.0 was evaluated during an official OPTEST at the Navy's Regional METOC centers at Norfolk (Naval Atlantic Meteorology and Oceanography Center - NLMOC) and San Diego (Navy Pacific Meteorology and Oceanography Center - NPMOC). The results of this OPTEST are stated in an OPTEST report to CNMOC (Appendix C) and re-iterated as part of an NRL proceedings paper at the MTS Oceans 2002 conference (Preller et al., 2002) (Appendix D).

This validation test report will describe the PCTides system and differences between PCTides 1.0 and 2.0. The report discusses the validation testing performed by NRL and includes (as appendices) the validation documentation generated by the outside experts and agencies described above.

A more detailed description of the PCTides system is available from the PCTides software documentation: Software Design Description (SDD) for the Globally Relocatable Navy Tide Model (PCTides 2.0), Software Requirements Specification (SRS) for the Globally Relocatable Navy Tide Model (PCTides 2.0), Software Test Description (STD) for the Globally Relocatable Navy Tide Model (PCTides 2.0) and User's Manual (UM) for the Globally Relocatable Navy Tide Model (PCTides 2.0).

The PCTides System

The PCTides system has a 2-dimensional (2-D) barotropic ocean model as its core (Figure 1). PCTides uses this depth-integrated shallow water model to predict both the barotropic currents and sea level heights on or near continental shelves (Preller et al., 2002). It contains a wetting and drying algorithm for the simulation of coastal flooding due to tides and/or storm surge. Surface winds, pressure and/or astronomical tidal forcing drive this model. A global tide model, the Finite Element Solutions 99 (FES99) is used to provide tidal conditions at the open boundaries of the ocean model.
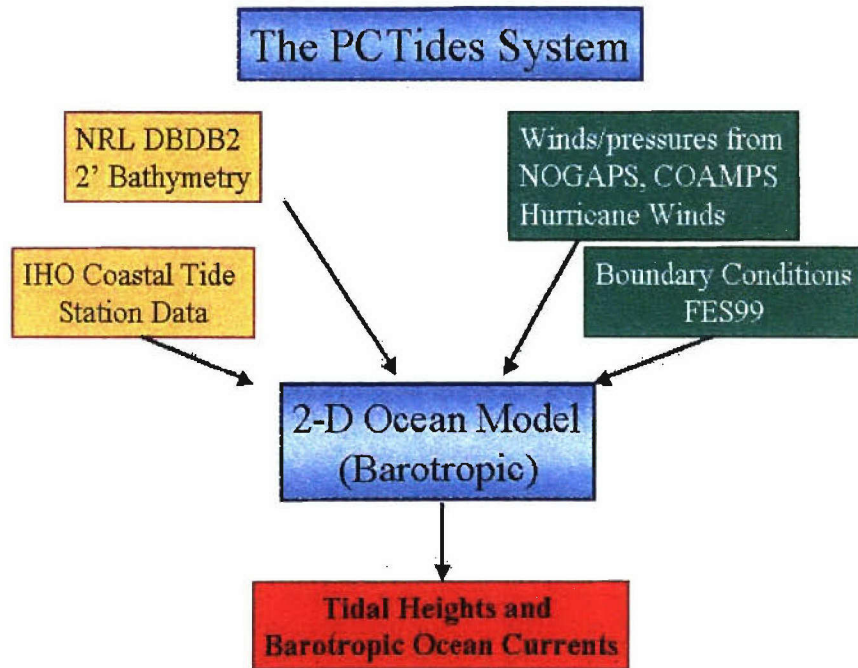
Figure 1. The PCTides system components.

All databases, except for the wind and pressure forcing, are internal to the PCTides system. These include: a) NRL generated bathymetry (NRL DBDB2), a 2-minute global data base (see http://www7320.nrlssc.navy.mil/DBDB2_WWW/) derived from a combination of the Navy's DBDBV data, the Smith and Sandwell dataset, the DAMEE North Atlantic data, the IBCAO Arctic data, the Australian Bathymetric and Topographic Data (ABTG), and regional data sets from the Gulf of Mexico and Yellow Sea; b) the FES99 global tidal solutions (Lefevre et al., 2000) and c) tidal station data from the International Hydrographic Office (IHO) database (Anonymous, 1988). The IHO data is used for either model validation or data assimilation.

In most applications of the system, winds from the Navy Operational Global Atmospheric Prediction System (NOGAPS) (Hogan and Rosmond, 1991), the Coupled Oceanographic and Atmospheric Mesoscale Prediction System (COAMPS™) (Hodur, 1997) or a COAMPS On-Scene system are used. These fields are used daily at the operational centers and retrieved typically through the Navy's METCAST system. In addition, the model contains a hurricane model (Holland, 1980) that generates hurricane force winds using a prescribed track, minimum surface pressure and radius of maximum winds. A final application of winds in the PCTides system is the input of a single value for wind speed over the entire domain which can vary temporally but not spatially, and is referred to as "manual winds" in the system.

Two dimensional fields of tidal heights and barotropic ocean currents are the products of the PCTides system. The user has the option of pre-selecting station locations where

high frequency (typically 10-12 minute) tidal time series forecasts may be produced. Stations are identified by latitude and longitude locations prior to the forecast. These time series are written to a file containing station information, date, time, tidal elevation, current speed and direction. The forecast may be viewed as a printed text file or plotted as a time series curve. In addition to the station forecasts, elevation and current data are saved at each model grid point at a pre-selected time interval with a minimum output frequency of 10 minutes.

PCTides can generate hindcasts back to the year 1900 (reference time chosen for the calculation of astronomical tides) and to any time in the future. Predictions that include wind/pressure forcing are limited to dates when the forcing is available. Tidal forecasts made without winds, can be useful in planning for future operational exercises.

PCTides is a depth-integrated, barotropic hydrodynamic model used for modeling sea surface height and mean current structure in coastal regions due to tides and atmospheric forcing. It is economic to run in terms of computational overhead and data initialization requirements.

A. Basic Equations of PCTides:

The equations solved are the shallow water equations and are presented below:

$$\frac{\partial U}{\partial t} = fV - mg\frac{\partial \zeta}{\partial x} - \frac{m}{\rho_\omega}\frac{\partial P}{\partial x} - m\left(U\frac{\partial U}{\partial x} + V\frac{\partial U}{\partial y}\right)$$
$$+ \frac{1}{\rho_\omega H}\left(\tau_{sx} - \tau_{bx} - \frac{\partial S_{xx}}{\partial x} - \frac{\partial S_{xy}}{\partial y}\right) - v\nabla^2 U,$$

(1.1)

$$\frac{\partial V}{\partial t} = -fU - mg\frac{\partial \zeta}{\partial y} - \frac{m}{\rho_\omega}\frac{\partial P}{\partial y} - m\left(U\frac{\partial V}{\partial x} + V\frac{\partial V}{\partial y}\right)$$
$$+ \frac{1}{\rho_\omega H}\left(\tau_{sy} - \tau_{by} - \frac{\partial S_{yx}}{\partial x} - \frac{\partial S_{yy}}{\partial y}\right) - v\nabla^2 V,$$

(1.2)

$$\frac{\partial \zeta}{\partial t} = -m^2\left[\frac{\partial}{\partial x}\left(\frac{UH}{m}\right) + \frac{\partial}{\partial y}\left(\frac{VH}{m}\right)\right],$$

(1.3)

where U and V are the depth averaged currents in the x and y directions respectively, H is the total depth, ζ is the surface elevation, f is the Coriolis parameter, g is the acceleration due to gravity, P is the atmospheric surface pressure, ρ_w is the water density, v is the coefficient of lateral eddy diffusion and has a value of 0.2, τ_{bx} and τ_{by}, the bottom frictional stress in the x and y directions, respectively. S_{xx}, S_{yy}, S_{xy} and S_{yx} represent the wave radiation stresses.

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The equations have been formulated on a Cartesian grid due to the relative ease of coding. However, the formulation is generalized to incorporate different map projections through the appropriate specification of the map factor, m, a scaling factor dependent on the chosen map projection of the model grid. In accordance with this generality, the Coriolis parameter varies with latitude.

The surface wind stress components are computed using the quadratic relationship:

$$\tau_{sx} = C_D \rho_a |\mathbf{u_a}| u_a, \qquad \tau_{sy} = C_D \rho_a |\mathbf{u_a}| v_a,$$

(1.4)

where $|\mathbf{u_a}| = \left(u_a^2 + v_a^2\right)^{\frac{1}{2}}$ u_a and v_a are the horizontal components of wind velocity at anemometer height, ρ_a is the density of air, and C_D is the drag coefficient based on Smith and Banke (1975) and expressed as follows:

$$C_D = [0.63 + 0.066|\mathbf{u_a}|] \times 10^{-3,} \qquad |\mathbf{u_a}| < 25 \, \text{m s}^{-1};$$
$$C_D = [2.28 + 0.033(|\mathbf{u_a}| - 25)] \times 10^{-3,} \qquad |\mathbf{u_a}| \geq 25 \, \text{m s}^{-1}.$$

(1.5)

The bottom stress is represented by a Manning's n depth-dependent friction relation following Signell and Butman (1992):

$$\tau_{bx} = \rho_w \frac{gn^2}{(H + \zeta)^{\frac{1}{3}}} \left(U^2 + V^2\right)^{\frac{1}{2}} U, \qquad \tau_{by} = \rho_w \frac{gn^2}{(H + \zeta)^{\frac{1}{3}}} \left(U^2 + V^2\right)^{\frac{1}{2}}$$

(1.6)

where n has the value 0.03. This formulation ensures that the drag coefficient increases with decreasing water depth and is applied to water depths greater than 1 m. In extremely shallow water and over land points that become inundated, drag coefficients can be specified at each grid-point according to the terrain type.

B. Boundary and Initial Conditions

Boundary conditions can be applied in a range of ways depending on the type of process being modeled. Meteorological forcing is applied via the wind stress and surface pressure gradient terms in equations (1.1) to (1.3) at all submerged model grid-points in the computational domain.

Tidal and meteorological forcing at lateral boundaries is achieved by specifying the incremental displacement of the water surface due to changes in tidal height and atmospheric barometric displacement. The lateral boundary conditions are applied using a "one-way nesting" technique. The boundary conditions are applied to the appropriate model variable ϕ (representing height or velocity) with decreasing intensity from the

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boundary to some specified number of model grid-points (typically around 12) into the domain according to the following equation;

$$\phi = (1-\alpha)\phi_p + \alpha\phi_b \tag{1.7}$$

where ϕ_p is the model predicted value and ϕ_b is the prescribed boundary value and α is varied according to a cosine function such that

$$\alpha = 0.5(\cos \pi(1-n/n_{max}) +1), \quad n=1, n_{max} \tag{1.8}$$

At coastal boundaries and along riverbanks, the wetting and drying of grid cells is accomplished via the inundation algorithm described in the next section. On outflow, a radiation boundary condition, as described in Miller and Thorpe (1981) is applied to the velocity field to prevent the build up of wave energy within the numerical domain, while on inflow boundaries, a zero-gradient condition is applied.

Under any prescribed boundary forcing, PCTides is initialized by setting velocities to zero and interpolates the global Finite Element Solutions versions 99 (FES 99) (Lefevre et al., 2000) elevation field to the model grid. It is customary to allocate an initial spin-up period to allow the effects of the boundary forcing and tidal conditions to propagate throughout the computational domain. Sensitivity studies conclude that an appropriate spin-up time for PCTides using wind forcing is 24 hours and without wind forcing is 12 hours.

C. Inundation Algorithm

The adjustment of coastlines to account for flooding and draining takes place after equations (1.1)-(1.3) have been solved as described above. The coastal boundary is configured to pass through the velocity grid-points on the staggered grid in a stepwise manner such that it passes through the U points in the y-direction and through V points in the x-direction. The velocities on the boundaries are assumed to be zero.

The first step is to calculate the distance in the x- and y-directions that fluid could travel in a time step at each ζ grid-point that is adjacent to the coast. The depth-averaged current velocity used in this calculation is taken at the first grid-point on the seaward side of the ζ grid-point. The travel distance is:

$$\Delta X_{i,j}^n = \begin{cases} \Delta X_{i,j}^n + \Delta t U_{i-1,j}^n, & U > 0 \\ \Delta X_{i,j}^{n-1} + \Delta t U_{i,j}^n, & U < 0 \end{cases} \tag{1.9}$$

$$\Delta Y_{i,j}^n = \begin{cases} \Delta Y_{i,j}^{n-1} + \Delta t V_{i,j-1}^n, & V > 0 \\ \Delta Y_{i,j}^{n-1} + \Delta t V_{i,j}^n, & V < 0 \end{cases} \tag{1.10}$$

where $\Delta X_{i,j}^{n-1}$ and $\Delta Y_{i,j}^{n-1}$ are the distances in the x and y directions that the water traveled in the previous time step. By factoring in the travel time of the fluid, inland grid cells are prevented from automatically becoming inundated at the first instant the water level at the coast exceeds the height of the adjacent dry points. In equations (1.9) and (1.10), the first option applies to flooding in the positive x or y direction (or draining in the negative x and y direction) while the second option applies to flooding in the negative x and y direction (or draining in the positive x and y direction).

The testing for coastline movement proceeds in the x- and y-directions separately. If the height of the water at the first z-point seaward of the coastline exceeds the topographic height at the first z-point landward of it, and the accumulated distance traveled in the given direction exceeds the grid separation, then a new sea-point is added to the computational domain. The velocity at the newly acquired velocity point is extrapolated from adjacent points and the continuity equation is solved to obtain the water depth at the new height point. Finally, $\Delta X_{i,j}^{n}$ and $\Delta Y_{i,j}^{n}$ are set to zero.

The procedure for draining is similar. If the height of the fluid at the height point adjacent the boundary drops below some arbitrary positive height, ε and the accumulated distance traveled by the fluid, exceeds the grid length, then draining is assumed to have occurred. The height grid-point is reclassified as dry (i.e. $\zeta = 0$) and the boundary relocated to the adjacent wet velocity grid-point. Examples of the performance of the inundation algorithm can be found in Hubbert and McInnes (1999a, b).

D. Tidal Data Assimilation

In order to improve the simulation of tidal forced dynamics a facility is included to "nudge" the model solution with tidal height predictions at tidal stations within the model domain. Global tidal station constituent data is stored in ASCII format in the file TCANALS.DAT. New stations can easily be added to this file in the appropriate format.

During a model run the TCANALS.DAT file is scanned by subroutine TIDEOBS during its first call and the tidal constituent parameters for stations within the model domain are stored. At each model time step the tidal height is predicted at each station and used to "nudge" the model solution.

The nudging method is based on deriving a new solution at grid points near each tidal station from a weighted combination of the model solution and the station sea level prediction. The weighting function is calculated from the product of the parameter WGTFAC (default value = 0.50) and the half cosine function (range = 0 to 1) used for nesting (equation 1.8). The weighting of the station sea level prediction goes to zero at a defined distance from each station, determined by the parameter ZRADIUS (default value = 40 km). The values of WGTFAC and ZRADIUS can be changed in the parameter file ASSIM.DAT that resides in the WORK directory. Changes to these parameters are not advised however unless there is a specific reason.

PCTides Operation

PCTides was developed to be used by METOC personnel who have some knowledge of oceanography. To apply PCTides, the user should know the latitude and longitude boundaries of their region of interest and the specific locations for which a forecast is required. The user first sets up a model "domain" by inputting the north/south limits of latitude and the east/west limits of longitude and the grid resolution (the PC version also contains a GUI based grid generator). This automatically generates the model grid and interpolates NRL DBDB2 bathymetry to that grid. Next, a user runs the program to interpolate the tidal boundary/initial conditions to the grid. All of this can be quickly plotted (bathymetry, tidal constituents, etc.) using the PC GUI. This allows the user to take a first look at the area of interest. The user inputs a series of parameters defining the forecast attributes such as start time and length of the forecast, data assimilation option (on or off), wind forcing and the required frequency of the model tidal output. In addition, the user identifies the specific stations at which a forecast field is needed by inputting the latitude and longitude of that station. The user then executes the model.

The PC version of this code includes a graphic capability to generate ".gif" plots of the forecast tidal time series. Along with tidal height forecasts, PCTides provides forecasts of 2-D barotropic tidal currents. A graphic capability to generate ".gif" plots of the forecast tidal speed and direction is also included with the PC version. The user should take caution in utilizing the current information since it is not the full, 3-D baroclinic ocean currents. The Unix version of the code has no output graphic package.

PCTides 1.0 versus PCTides 2.0

PCTides 1.0 was originally submitted to OAML in 2002. However, this version was developed for use on a PC and as such did not comply with the OAML standard of only accepting UNIX software for transition. During FY03, NRL revised the PCTides model into a standardized UNIX code that could also be applied to a PC with either Windows 2000 or XP operating systems. While modifying the PCTides system, NRL incorporated some additional improvements to the code. These include: a) replacing the FES 95.2.1 (0.5 degree) global boundary conditions with the FES 99 (0.25 degree) global boundary conditions (see Figure 2), b) UNIX and PC grid generation software (input latitude/longitude limits of the grid domain and resolution), c) adding the latest version of NRL DBDB2 bathymetry, d) modifying the bathymetry interpolation algorithm (UNIX and PC versions now are identical), e) increasing the maximum array size, f) adding software to automatically move specified output stations that are on land (due to numerical model grid resolution), to the closest ocean grid point, g) modifying the frequency of field output, h) increasing bottom friction for high resolution nests, i) adding code to incorporate new high resolution bathymetric data, j) adding error messages to parts of the code to make it more user friendly and k) modifying the documentation to reflect these changes. As such, these changes were substantial enough to warrant withdrawing PCTides 1.0 from OAML and delivering the new PCTides 2.0 in its place.

One of the revisions of the PCTides upgrade included the improvement to the global boundary conditions from the Finite Element Solution (FES) model. The major difference between the FES95 and FES99 is the resolution of the data. Also the accuracy of the FES99 solutions was improved by assimilating tide gauge and Topex/Poseidon altimeter information. The data used in PCTides 1.0 was FES 95, with a resolution of 0.5 degree. It contained both amplitude and phases of nine major tidal components. PCTides 2.0 was upgraded to use the FES99 data. This dataset has 0.25 degree resolution and assimilates 687 TOPEX/Poseidon altimetry crossover data along with ~ 700 tide gauge data in the database. It contains both amplitude and phases for the nine major tidal components and is a significant improvement both in the deep ocean and along the coasts.

Globally, the maximum M2 (the major constituent of the nine used in the model) phase differences (figure 2a) are very small but with most differences occurring in the Bering Strait, Hudson Bay and Gulf of Lawrence (figure 2b), in the western Antarctic (figure 2c), and around Australia and the Indonesia coast (figure 2d). The other limited areas where differences occur include the southeast Mediterranean, the Iceland area, and the Kara and Laptev Sea. Neither FES95 nor FES99 have values in the Black or Caspian Seas. The amplitude differences are very small in most areas.
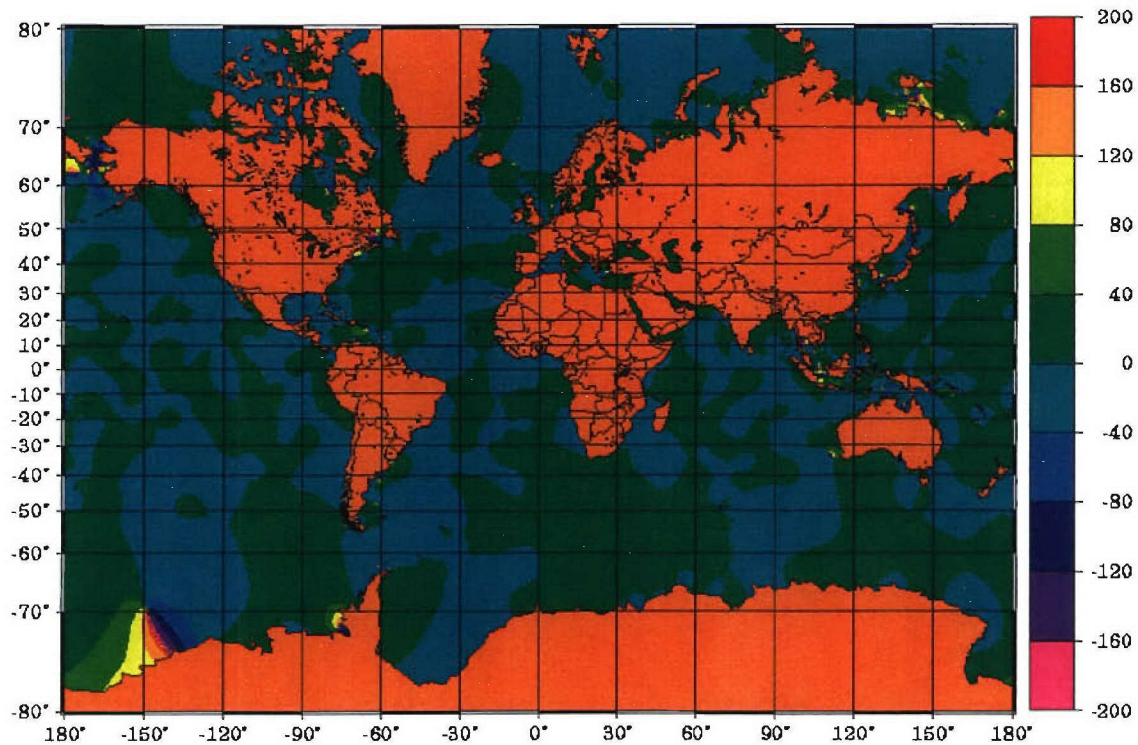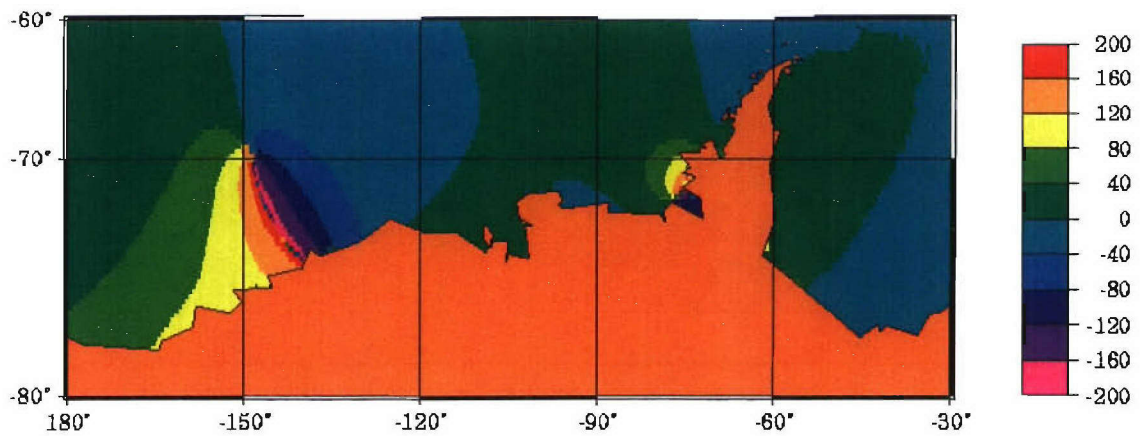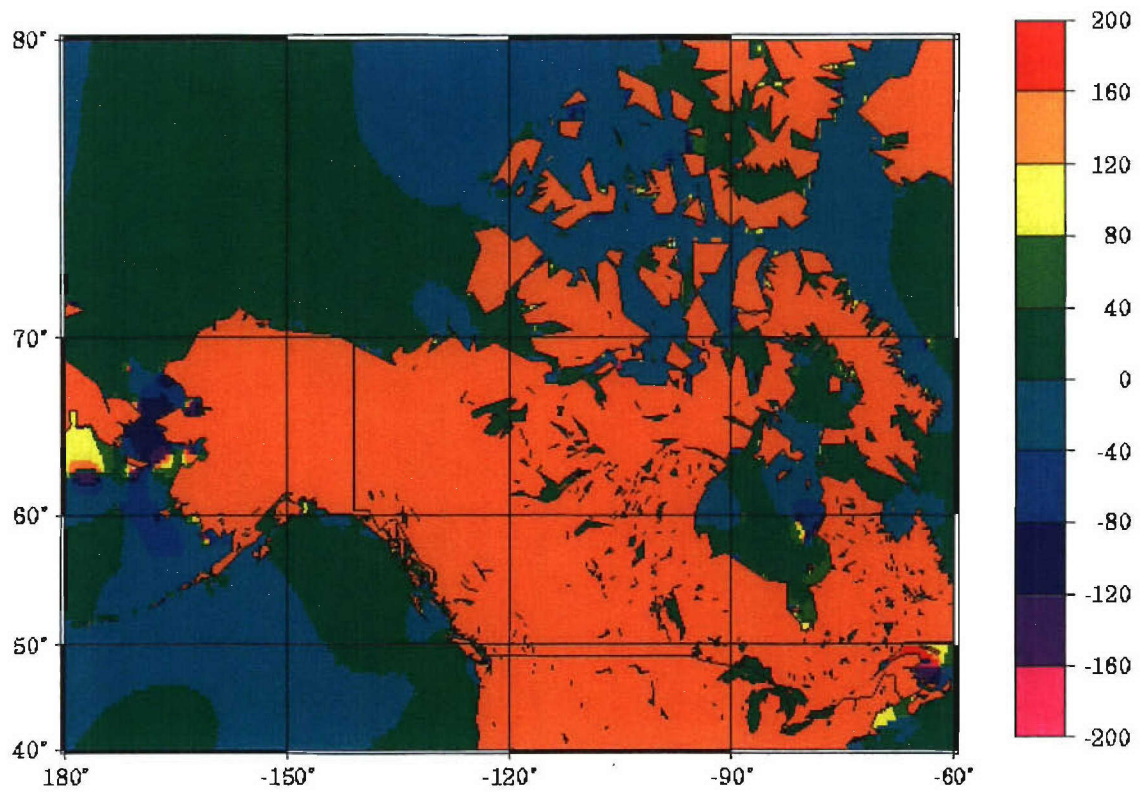

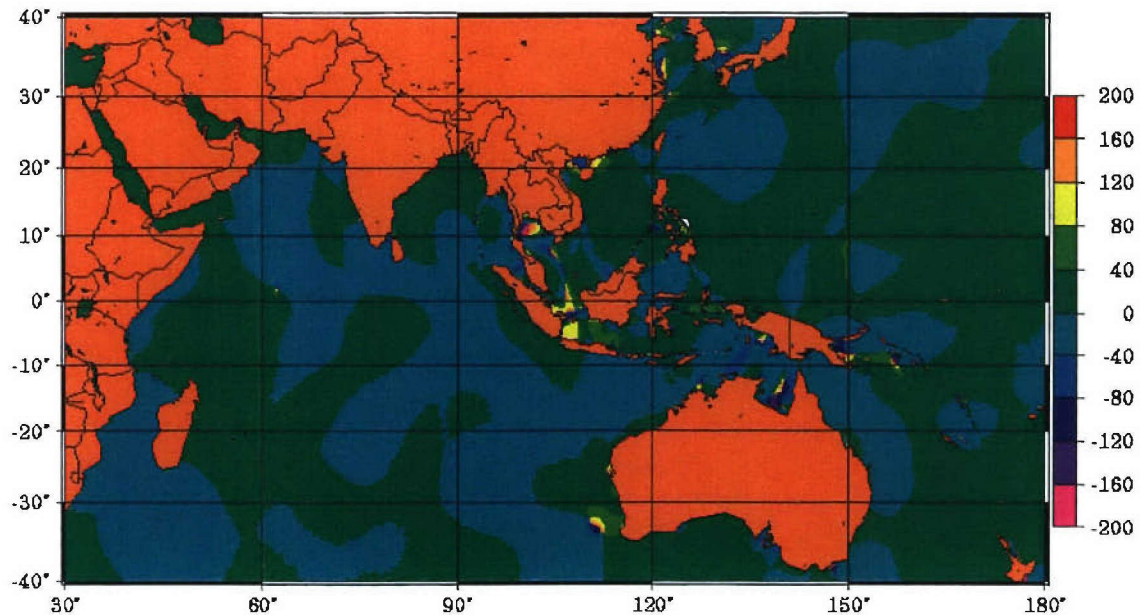Figure 2a. World M2 Phase Difference (in degrees) between FES99 and FES95.

Figure 2b: Bering Strait, Gulf of St. Lawrence and Hudson Bay area
M2 phase differences

Figure 2c: Western Antarctic M2 phase differences

Figure 2d: Australia and the Indonesia coast M2 phase differences

PCTides Evaluation

A majority of the PCTides evaluations were performed using PCTides 1.0. However, those specific evaluations were only minimally (if at all) affected by the modifications included in PCTides version 2.0 and as such are believed to still be valid. If anything, errors should be reduced.

The PCTides OPTEST evaluation was performed by the regional centers at Norfolk (NLMOC) and San Diego (NPMOC). NLMOC chose the Chesapeake Bay as their evaluation location while NPMOC chose three regions for evaluation: 1) Scripps located off the southern California coast, 2) an area near Puget Sound and 3) near the Gulf of Alaska. The pass/fail criteria determined prior to the OPTEST by the centers, were an RMS error of less than 1.2 ft (0.365 m) in amplitude and a phase error less than 45 minutes. PCTides successfully passed this OPTEST in each area studied as documented in the OPTEST report (Appendix C) and the Preller et al., 2002 (Appendix D).

In addition to the OPTEST, PCTides was run for the region encompassing the southwestern coast of Spain. These runs were initially performed by NRL as part of a Rapid Response (RR98) Exercise off the Spainist coast in 1998 using PCTides 1.0 system. Figure 3 shows the model domain used and the specified output stations.
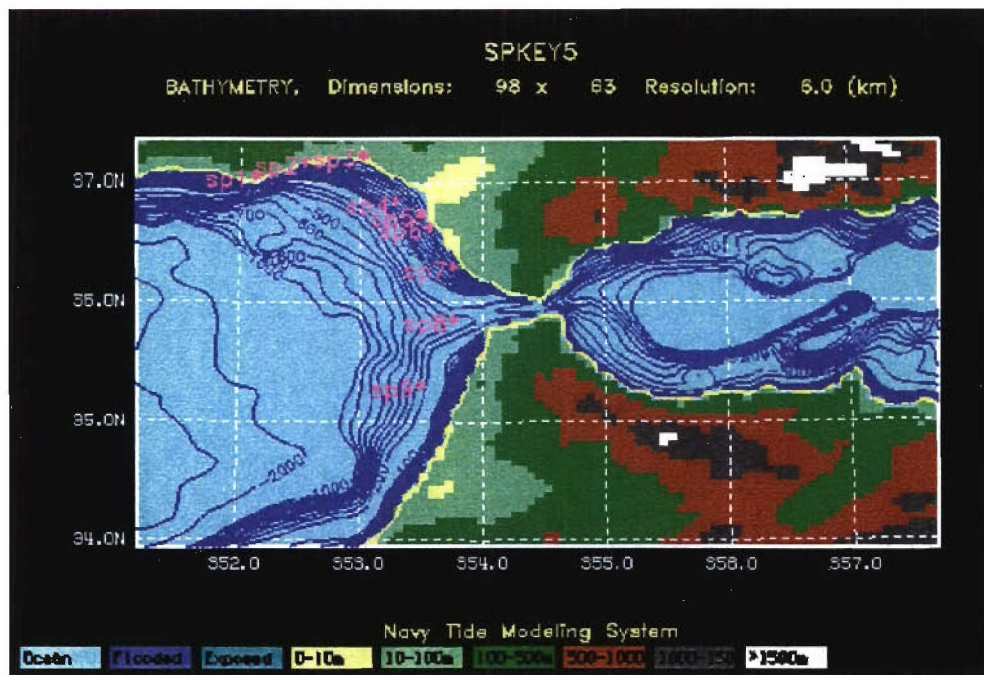
Figure 3.   Model domain with bathymetry contours and station locations for the southwestern coast of Spain.

The model simulations were run without IHO data assimilation and compared to the closest IHO data point for evaluation. Figures 4-6 show the comparisons of a 5-day (120 hour) elevation forecast from PCTides to the closest IHO point at stations 1, 3, and 6 (6 being closest to the Navy's regional center at Rota, NEMOC). This forecast was for December 4, 2003 – Dec 9, 2003.
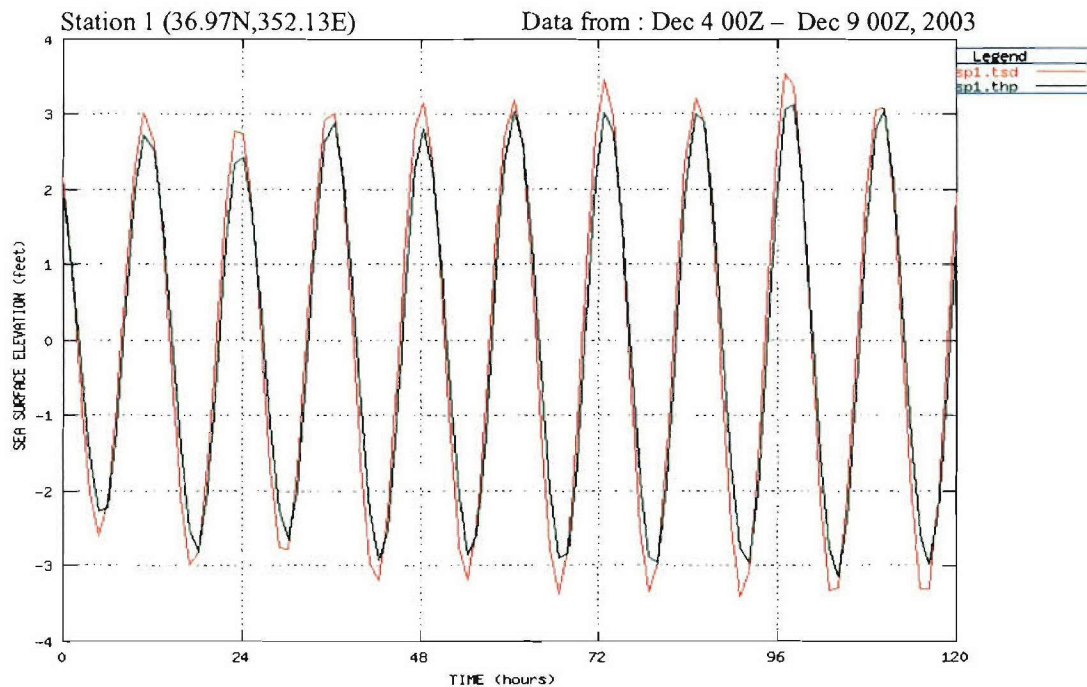

Figure 4. Tidal height time series at station 1 for PCTides (red) and IHO (green) valid for December 4 – 9, 2003.
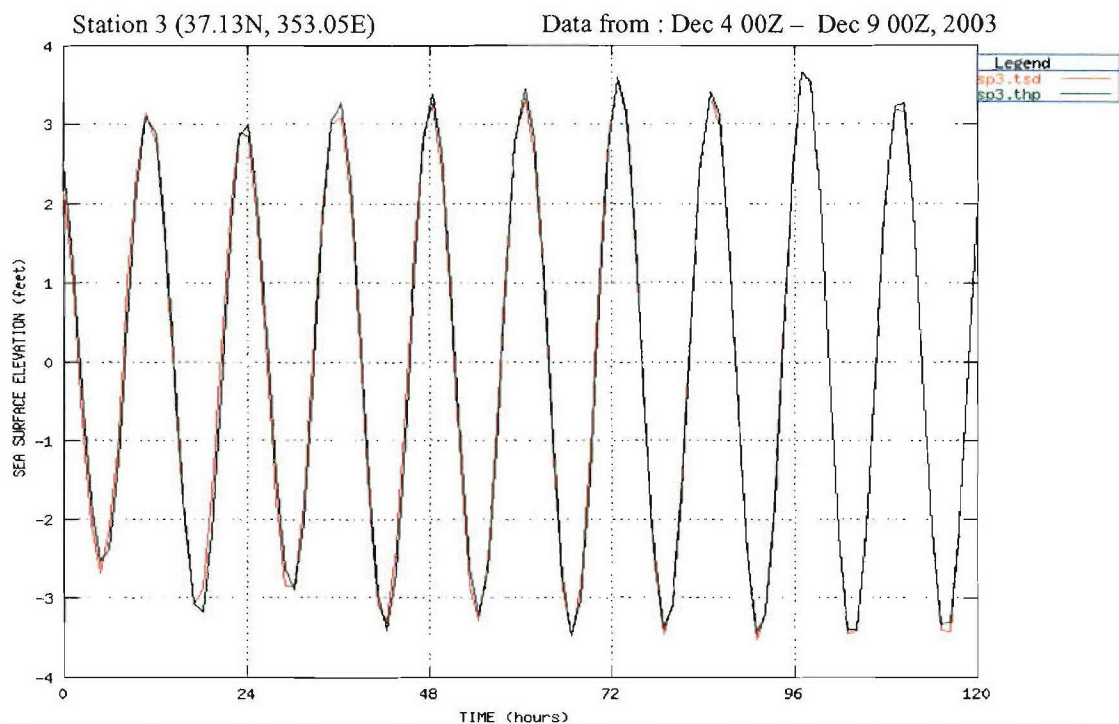
Figure 5. Tidal height time series at station 3 for PCTides (red) and IHO (green) valid for December 4 – 9, 2003.
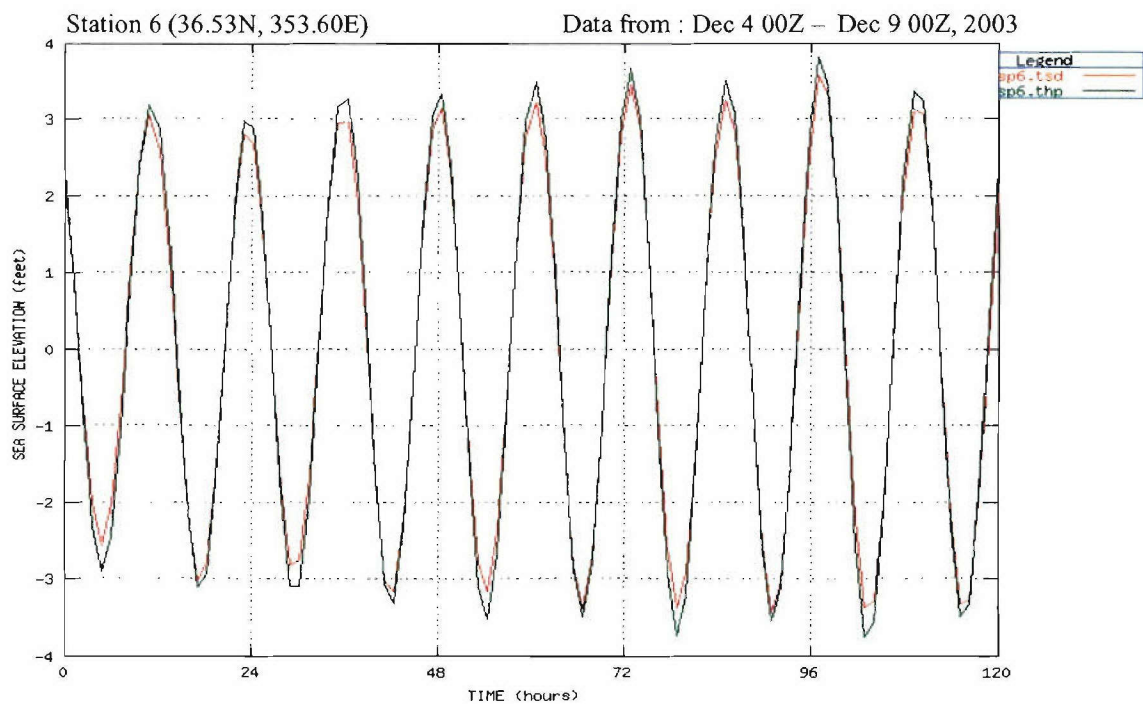

Figure 6. Tidal height time series at station 6 for PCTides (red) and IHO (green) valid for December 4 – 9, 2003.

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Similar results presented at the RR98 Hot Wash meeting at Saclant Centre in La Spezia, Italy and at the 1999 US/UK Operational Oceanography workshop held in Taunton, England had been seen by NEMOC personnel. As a result, NEMOC requested to serve as a beta-tester of PCTides. PCTides was installed on their system in January 1999 and upgraded in August 2002. NEMOC successfully generated and distributed PCTides solutions to their users (see Appendix A) until the closure of the base.

Dr. Roger Proctor of the Proudman Oceanographic Laboratory performed an additional assessment of PCTides. Dr. Proctor and his colleagues are acknowledged experts in the prediction of tides in the NW European shelf region. Dr. Proctor worked with NRL to set up a PCTides grid similar to that used by the UK model. Tides and surges from PCTides were compared to the UK model output and to observations for the period April-May, 2001. Dr. Proctor concluded that PCTides forecast, assimilating IHO data, contained the same order of accuracy as the "tuned" UK model (Appendix B). Without IHO data assimilation, PCTides performance was less accurate than the UK model.

Although the main focus of these evaluations has been on tidal elevation, PCTides also predicts 2-D barotropic tidal currents. A major obstacle in evaluating the PCTide tidal currents is the lack of observations to compare against the model results. However, an excellent opportunity to validate the models forecast velocities was presented to us when the Naval Oceanographic Office provided us the data from four bottom mounted Acoustic Doppler Current Profilers (ADCP) in the Yellow Sea deployed during the month of September 1995 (Figure 7). This thirty-day time series of velocity data was compared to a PCTides model forecast, which assimilated IHO data, but had no wind or pressure forcing. The PCTides forecasts of the tidal currents agree remarkably well with the depth-averaged ADCP observations. The last five days are shown (Figure 8). Comparisons of the tidal heights for the entire time show the accuracy of PCTides forecast capability (Figure 9) as compared to the water level elevations derived from pressure gauges on the ADCP.

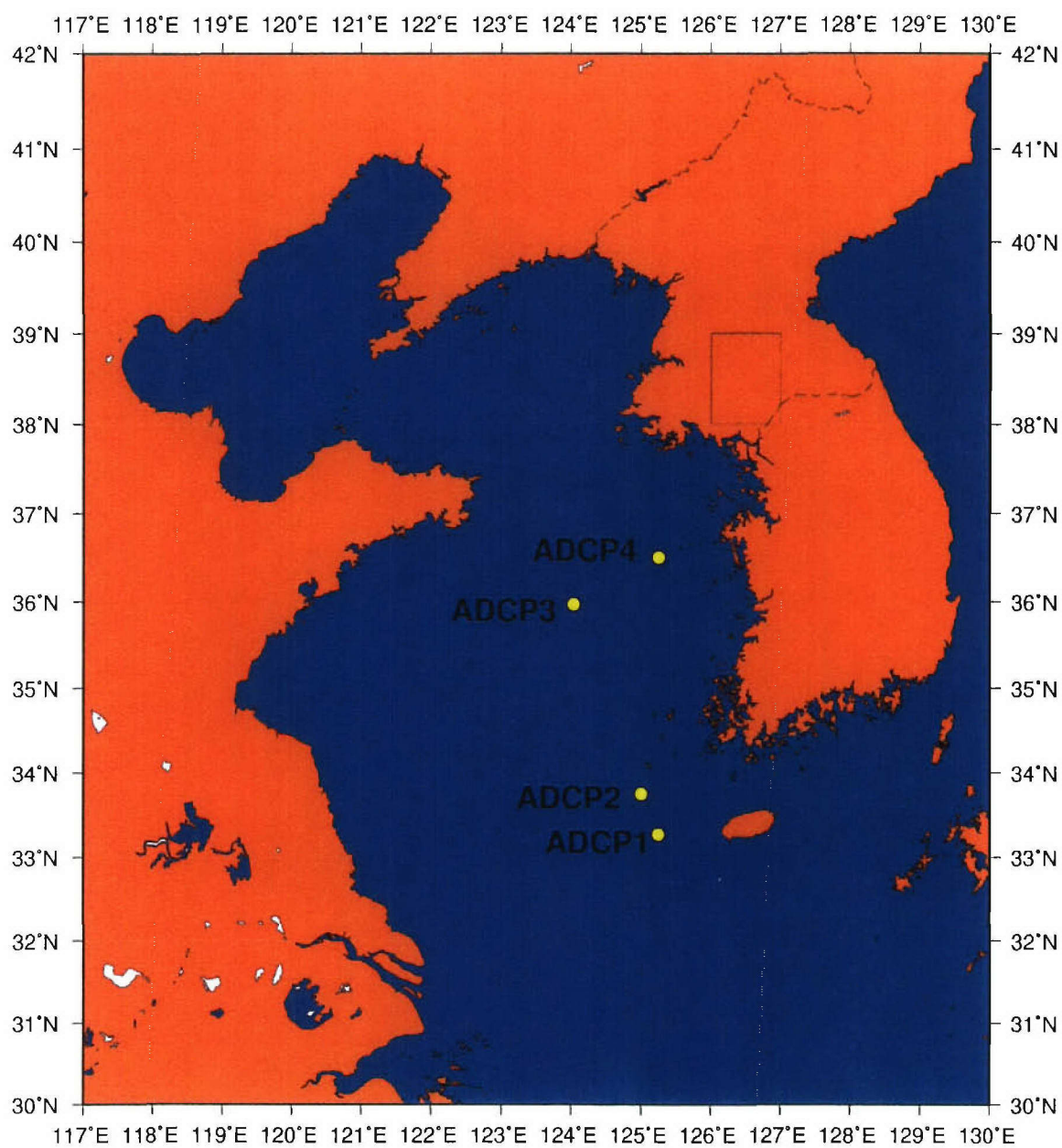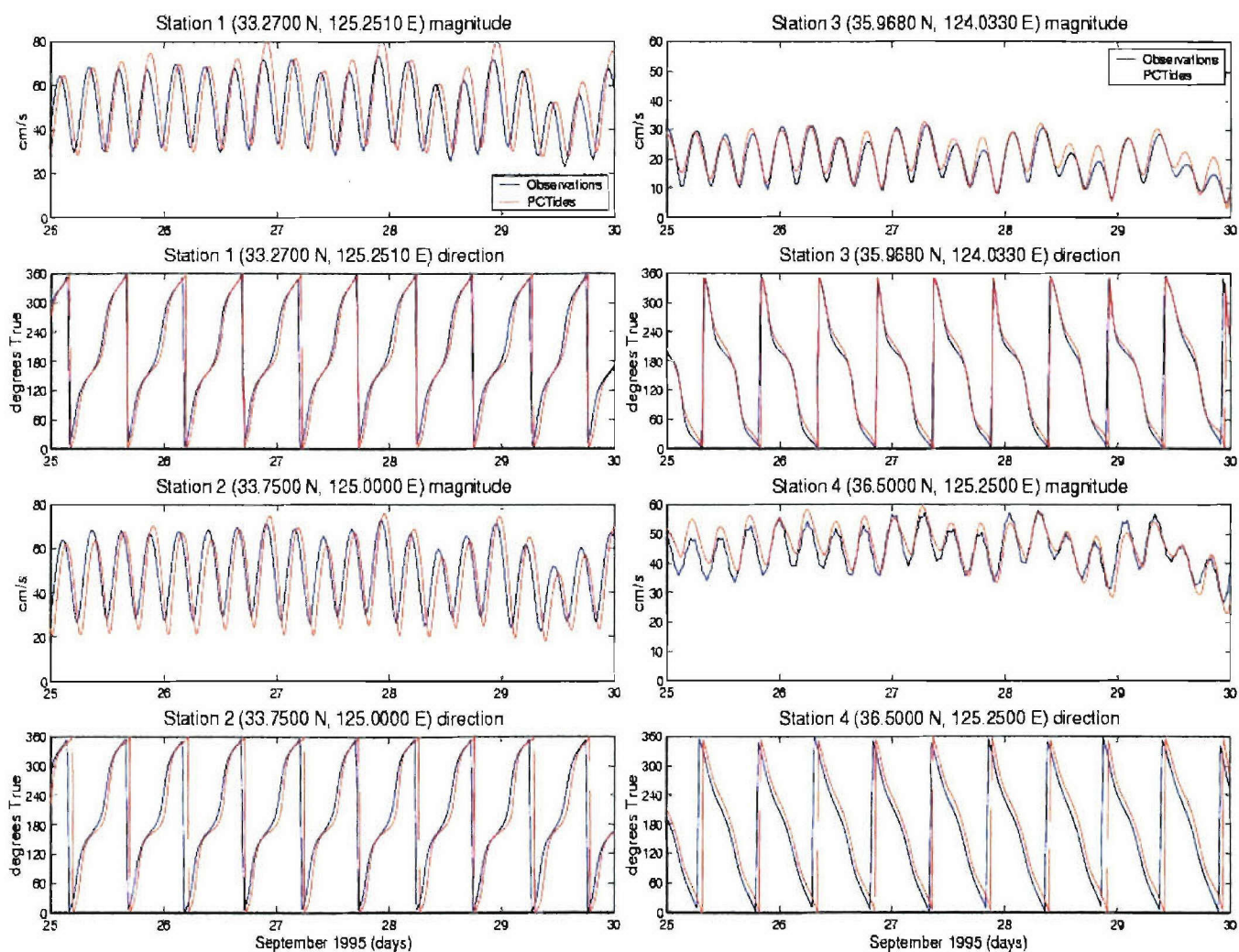Figure 7. ADCP locations in the Yellow Sea during September 1995.

Figure 8. PCTides 2-D Barotropic tidal current forecast (red) versus the depth-averaged ADCP observation (blue) of current magnitude and direction at ADCP locations for the period September 25-30, 1995.
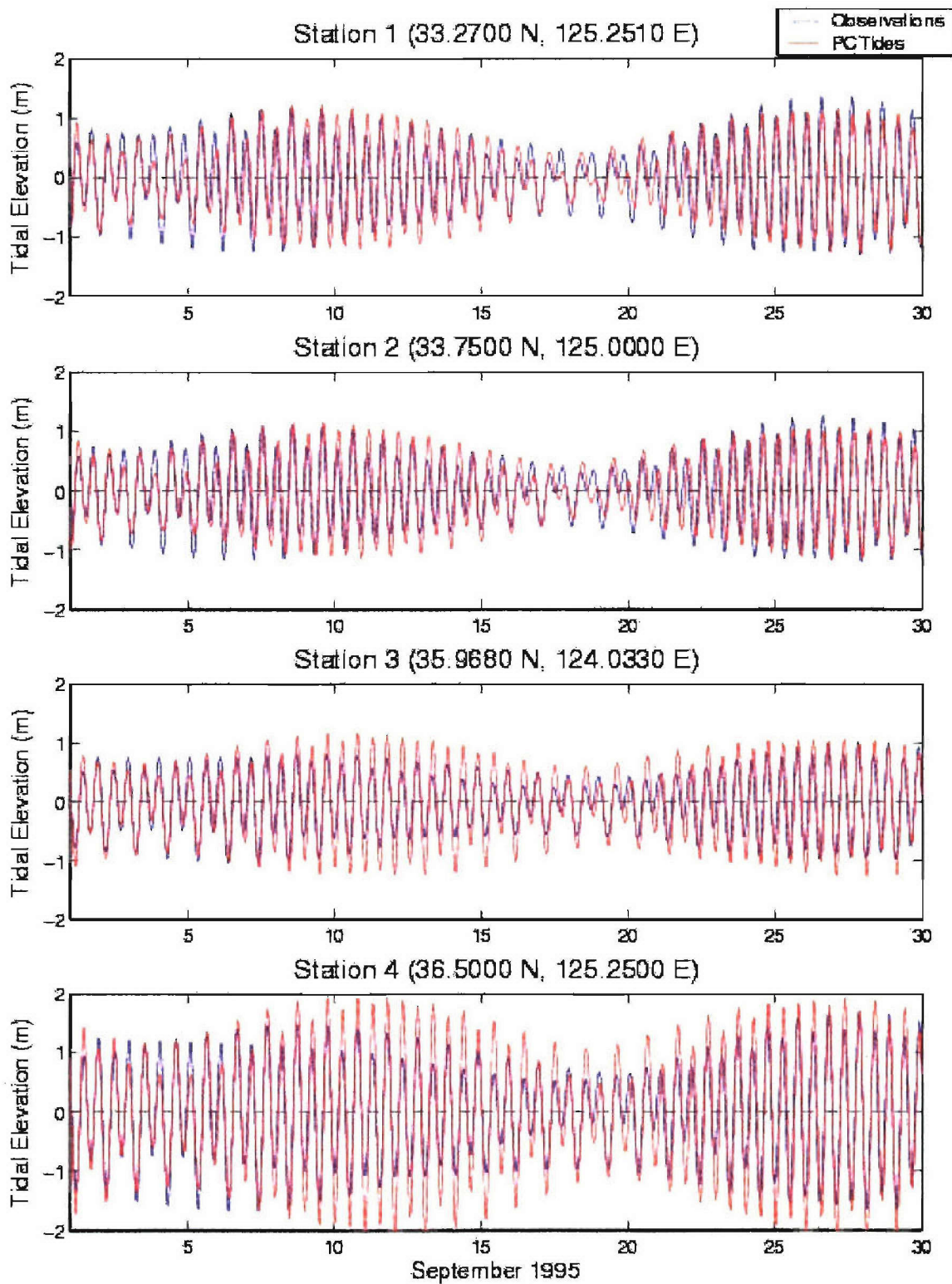
Figure 9. PCTides (red) versus the ADCP observations (blue) of the water level at stations 1 − 4 for the period September 1- 30, 1995.

A statistical evaluation of the PCTide tidal elevation and phase along with tidal magnitude were compared to the ADCP observations. The ADCP observations were not assimilated into the PCTides forecast but used only for validation. The statistics shown are the mean error (ME), absolute mean error (AME), root mean square difference (RMSD), standard deviation (SD), the correlation coefficient (R) and the skill score (SS).

The statistics are computed from the following equations:

$$ME = \bar{Y} - \bar{X}, \quad where \ \bar{X} = 1/n \sum_{i=1}^{n} X_i \tag{1}$$

$$AME = 1/n \sum_{i=1}^{n} |Y_i - X_i| \tag{2}$$

$$RMSD = [1/n \sum_{i=1}^{n} (Y_i - X_i)^2]^{\frac{1}{2}}, \tag{3}$$

$$SD = [1/n \sum_{i=1}^{n} (X_i - \bar{X_i})^2], \tag{4}$$

$$R = 1/n \sum_{i=1}^{n} (X_i - \bar{X})(Y_i - \bar{Y})/ (\sigma_x \sigma_y), \tag{5}$$

$$SS = R^2 - [R - (\sigma y/\sigma x)]^2 - [(\bar{Y} - \bar{X})/ \sigma_x]^2, \tag{6}$$

Where ME is the bias or annual mean difference, $\bar{X}$ is mean of the data values, $\bar{Y}$ is the mean of the model values, SD is the standard deviation and σ_x and σ_y are the standard deviation of the data and model values respectively. For the mean difference (ME), the smaller the number, the smaller the difference between the model and the data. However, if the mean is near zero, as one would expect for a tidal time series, then the mean error is not a good statistical tool to use. The lower the absolute mean difference (AME), the smaller the variability between the observation and the model. This value expresses the mean difference between the model and the observations. The Root Mean Square (RMS) difference reflects the variability between the observation and the data. This is the classic expression of how close the model solution is to the observations. The larger the variability between the observations, the larger the RMS error. Like the RMS, the standard deviation (SD) gives you the variability of the data from the mean. As SD and RMS increase, the larger the variability of the data from the mean. A skill score (SS) of 1.0 indicates a perfect model prediction. A negative skill score indicates that the model may have normalized amplitudes larger than the correlation or large biases in the mean (Murphy and Epstein, 1989).

Table 1 shows the tidal elevation statistics for the mean of both the model (with and without data assimilation) and the observations, the standard deviation of the model and the observations, the mean error (ME) difference, root mean square difference (RMSD) correlation coefficient (R) and the skill score (SS). The value in the parentheses is the PCTides model forecast without any type of data assimilation.

Tidal Elevation (cm)

Station	Mean(model)	Mean(obs)	SD(model)	SD(obs)
Location 1	-0.49 (0.08)	1.37	52.06 (63.42)	63.00
Location 2	-0.70 (-0.03)	1.11	54.56 (63.43)	58.73
Location 3	-0.31 (0.16)	0.24	59.84 (49.49)	50.55
Location 4	-0.35 (0.05)	0.64	106.41 (86.82)	84.37

Station	Mean Diff	RMS Diff	Corr Coeff	Skill Score
Location 1	-1.86 (-1.29)	45.14 (47.41)	0.71 (0.72)	0.49 (0.43)
Location 2	-1.81 (-1.14)	43.98 (44.25)	0.70 (0.74)	0.44 (0.43)
Location 3	-0.55 (-0.08)	30.86 (31.25)	0.86 (0.81)	0.63 (0.62)
Location 4	-0.99 (-0.59)	50.32 (52.96)	0.89 (0.81)	0.64 (0.61)

Table 1. Mean of model and observations Standard Deviation of model and observations Mean Error Difference (ME), Root Mean Squared Difference (RMSD), Correlation Coefficient and Skill Score associated with amplitude of peak tidal elevations for PCTides results (with and without assimilation) compared to ADCP observations.

This comparison indicates the PCTides tidal elevation results using data assimilation compared better to the actual observations than the PCTides results without data assimilation (values in parenthesis). The RMS difference reflects the variability between the observations and the PCTides model. In this test study area using the RMS differences as our guide, the PCTides (with assimilation) varied slightly less from the observations by 30-50 cm, than the PCTides (without assimilation), which varied 31-53 cm. Comparing the correlation coefficients, the PCTides with assimilation ranged between 0.70 and 0.89, compared best to observations than the PCTides without assimilation that ranged between 0.72 and 0.81. A correlation coefficient of 1.0 indicates a perfect comparison.

Table 2 shows the absolute mean error (AME), root mean squared (RMS) and the correlation associated with the phase of peak tidal elevation (in minutes). Table 3 shows the tidal speed magnitude statistics for the mean for both the model and the observations the standard deviation of the model and the observations, the mean error (ME) difference, root mean square difference (RMSD), correlation coefficient (R) and the skill score (SS). The value in the parentheses (in all three tables) is the PCTides model forecast without any type of data assimilation.

Tidal Elevation Phase (minutes)

Station	AME	RMS
Location 1	96.61 (96.88)	102.11 (102.64)
Location 2	98.21 (87.24)	102.69 (93.08)
Location 3	53.70 (69.65)	60.65 (78.73)
Location 4	41.61 (72.21)	49.34 (81.26)

Table 2. Absolute Mean Error (AME) and Root Mean Squared (RMS) associated with the phase (in minutes) of peak height elevations for PCTides (with and without assimilation) results compared to ADCP observations.

Tidal Speed Magnitude (cm/sec)

Station	Mean(model)	Mean(obs)	SD(model)	SD(obs)
Location 1	32.86 (28.65)	38.53	12.86 (14.11)	16.02
Location 2	31.29 (29.60)	37.83	13.86 (16.24)	16.06
Location 3	16.59 (16.28)	16.34	6.00 (8.73)	7.25
Location 4	33.94 (28.68)	35.26	10.49 (10.45)	10.73

Station	Mean Diff	RMS Diff	Corr Coeff	Skill Score
Location 1	-5.67 (-9.89)	12.81 (16.64)	0.70 (0.61)	0.36 (-0.08)
Location 2	-6.54 (-8.22)	10.97 (15.95)	0.84 (0.64)	0.53 (0.01)
Location 3	0.25 (-0.06)	4.39 (5.14)	0.80 (0.81)	0.63 (0.50)
Location 4	-1.31 (-6.58)	6.70 (11.68)	0.81 (0.59)	0.61 (-0.18)

Table 3. Mean of model and observations, Standard Deviation of model and observations Mean Error Difference (ME), Root Mean Squared Difference (RMSD), Correlation Coefficient and Skill Score associated with phase of peak tidal elevations for PCTides results (with and without assimilation) compared to ADCP observations.

The second set of measurements used in the evaluation of PCTides ocean currents was located in the Korea (Tsushima) Strait. Figure 10 shows the location of the two lines of bottom mounted ADCP's as part of the NRL Linkages of Asian Marginal Seas (LINKS) program. A PCTides domain was set up for this region and run for the period May 1-June 11, 1999. PCTides forecast tidal currents were compared to tidal current measurements from the ADCPs. Figure 11 shows examples from six stations at opposite ends of each line. PCTides consistently under predicted the magnitude of the currents located at stations L1-L5 anywhere from 1-23% (0.2 to 3.3 cm/sec) and over predicted the magnitude of the currents located at stations L6-L11 anywhere from 5-27% (0.6 to 3.5 cm). Current direction compared reasonably well at all stations.
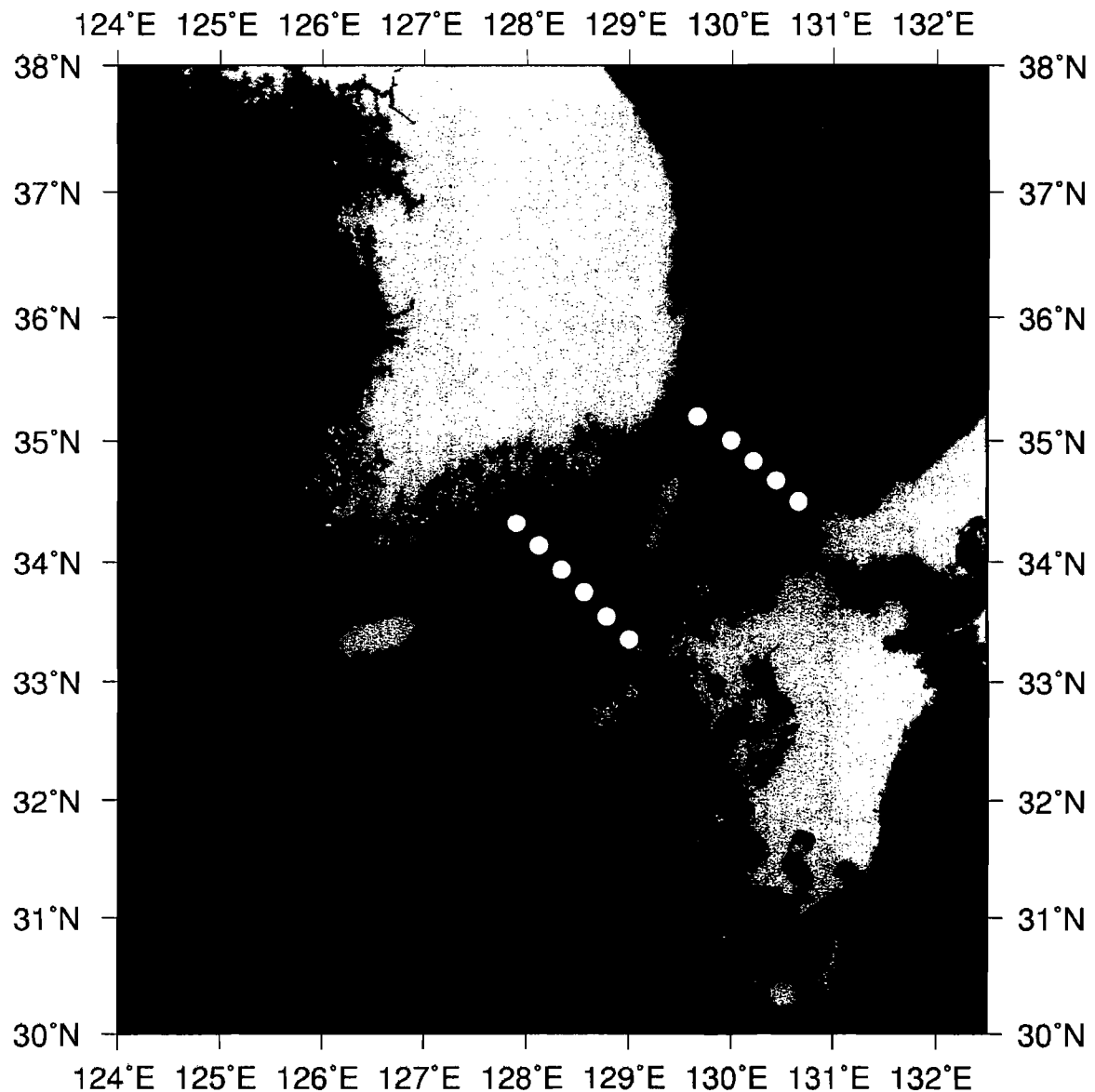

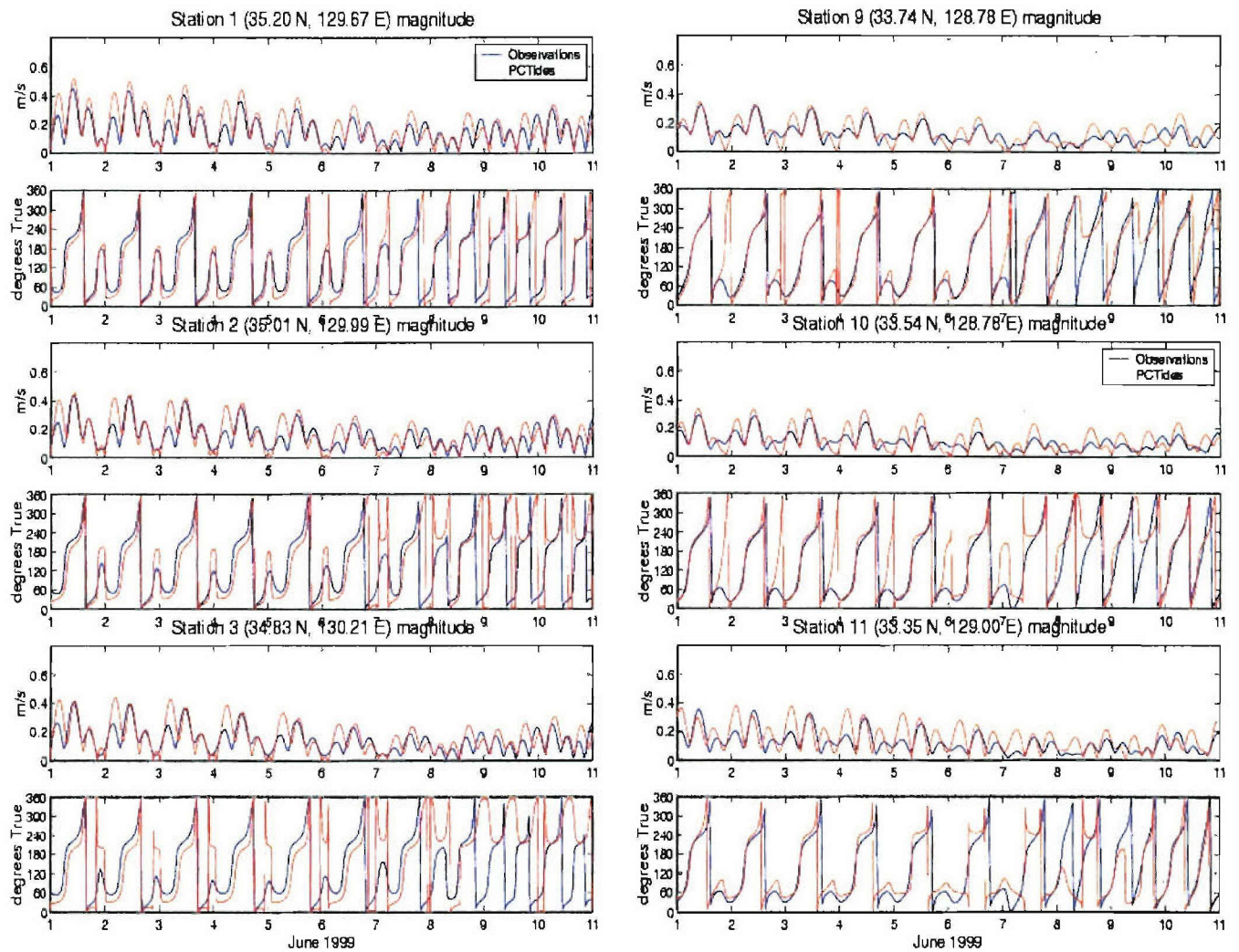Figure 10. Location of bottom mounted ADCP's in the Korea Strait.

Figure 11. PCTides 2-D Barotropic tidal current forecast (red) versus the depth-averaged ADCP observations (blue) of current magnitude and direction at stations indicated for the period June 1-11, 1999.

Table 4 shows the tidal elevation statistics for the mean for both the model (with and without data assimilation) and the observations, the standard deviation of the model and the observations, the mean error (ME) difference, root mean square difference (RMSD) correlation coefficient (R) and the skill score (SS). The value in the parentheses (in all three tables) is the PCTides model forecast without any type of data assimilation.

Tidal Elevation (cm)

Station	Mean(model)	Mean(obs)	SD(model)	SD(obs)
Location 1	-0.11 (0.06)	0.03	11.48 (17.55)	13.47
Location 2	0.51 (0.11)	0.05	12.23 (17.52)	14.64
Location 3	0.73 (0.16)	0.06	14.30 (19.31)	16.14
Location 4	1.00 (0.20)	0.07	16.70 (21.22)	17.90
Location 5	1.55 (0.30)	0.08	19.39 (22.93)	19.99
Location 6	0.01 (0.31)	0.21	65.35 (83.11)	67.63
Location 7	0.36 (0.28)	0.20	60.88 (77.64)	62.88
Location 8	0.92 (0.34)	0.19	57.75 (73.26)	59.91
Location 9	1.23 (0.32)	0.18	56.84 (71.03)	58.40
Location 10	1.06 (0.27)	0.18	56.89 (70.25)	58.04
Location 11	1.05 (0.31)	0.18	59.51 (71.41)	58.26

Station	Mean Diff	RMS Diff	Corr Coeff	Skill Score
Location 1	-0.14 (0.03)	5.38 (8.29)	0.92 (0.89)	0.84 (0.62)
Location 2	0.46 (0.06)	6.51 (7.74)	0.90 (0.90)	0.80 (0.72)
Location 3	0.67 (0.10)	7.18 (7.96)	0.90 (0.91)	0.80 (0.76)
Location 4	0.93 (0.13)	7.92 (8.34)	0.90 (0.92)	0.80 (0.78)
Location 5	1.47 (0.22)	9.20 (9.02)	0.89 (0.92)	0.79 (0.80)
Location 6	- 0.21 (0.10)	17.89 (34.72)	0.96 (0.91)	0.93 (0.74)
Location 7	0.16 (0.08)	17.51 (32.37)	0.96 (0.92)	0.92 (0.74)
Location 8	0.73 (0.16)	16.89 (29.63)	0.96 (0.92)	0.92 (0.76)
Location 9	1.05 (0.14)	17.26 (28.52)	0.96 (0.92)	0.91 (0.76)
Location 10	0.88 (0.09)	18.05 (28.22)	0.95 (0.92)	0.90 (0.76)
Location 11	0.86 (0.13)	21.37 (29.07)	0.93 (0.92)	0.87 (0.75)

Table 4. Mean of model and observations, Standard Deviation of model and observations Mean Error Difference (ME), Root Mean Squared Difference (RMSD), Correlation Coefficient and Skill Score associated with amplitude of peak tidal elevations for PCTides results (with and without assimilation) compared to ADCP observations.

Table 5 shows the tidal speed magnitude statistics for the mean for both the model and the observations, the standard deviation of the model and the observations the mean error (ME) difference, root mean square difference (RMSD) correlation coefficient (R) and the skill score (SS). The value in the parentheses (in all three tables) is the PCTides model forecast without any type of data assimilation.

Tidal Speed Magnitude (cm/sec)

Station	Mean(model)	Mean(obs)	SD(model)	SD(obs)
Location 1	0.17 (0.23)	0.17	0.10 (0.13)	0.10
Location 2	0.14 (0.21)	0.16	0.08 (0.11)	0.09
Location 3	0.12 (0.19)	0.15	0.07 (0.10)	0.09
Location 4	0.11 (0.16)	0.14	0.07 (0.10)	0.09
Location 5	0.11 (0.18)	0.15	0.07 (0.11)	0.10
Location 6	0.18 (0.25)	0.15	0.11 (0.11)	0.08
Location 7	0.13 (0.18)	0.13	0.07 (0.09)	0.07
Location 8	0.13 (0.16)	0.12	0.07 (0.08)	0.06
Location 9	0.13 (0.15)	0.13	0.07 (0.06)	0.06
Location 10	0.13 (0.13)	0.11	0.08 (0.07)	0.06
Location 11	0.16 (0.14)	0.13	0.10 (0.09)	0.07

Station	Mean Diff	RMS Diff	Corr Coeff	Skill Score
Location 1	-0.00 (0.05)	0.06 (0.09)	0.82 (0.83)	0.65 (0.17)
Location 2	-0.03 (0.04)	0.06 (0.07)	0.78 (0.85)	0.53 (0.39)
Location 3	-0.03 (0.03)	0.07 (0.07)	0.70 (0.79)	0.36 (0.31)
Location 4	-0.03 (0.02)	0.07 (0.07)	0.69 (0.79)	0.33 (0.45)
Location 5	-0.03 (0.03)	0.08 (0.08)	0.65 (0.75)	0.31 (0.30)
Location 6	0.03 (0.10)	0.06 (0.12)	0.89 (0.86)	0.49 (-0.89)
Location 7	0.01 (0.05)	0.04 (0.07)	0.88 (0.87)	0.76 (0.23)
Location 8	0.01 (0.04)	0.03 (0.05)	0.90 (0.91)	0.69 (0.24)
Location 9	-0.00 (0.02)	0.03 (0.03)	0.92 (0.95)	0.80 (0.81)
Location 10	0.01 (0.02)	0.05 (0.03)	0.82 (0.93)	0.28 (0.68)
Location 11	0.03 (0.02)	0.07 (0.04)	0.78 (0.93)	-0.07 (0.68)

Table 5. Mean of model and observations Standard Deviation of model and observations, Mean Error Difference (ME), Root Mean Squared Difference (RMSD), Correlation Coefficient and Skill Score associated with phase of peak tidal elevations for PCTides results (with and without assimilation) compared to ADCP observations.

A study was performed of the storm surge associated with Hurricane Isabel (Preller et al., 2005) using PCTides 2.0. In this study, PCTides was driven by winds and sea level pressure values from COAMPS, NOGAPS and the hurricane model included in PCTides (Holland, 1980). PCTides was not constrained to any observations during these studies. The PCTides predicted storm surge from these cases was compared to the NOAA observed water levels at stations along the path of Isabel. Figure 12 shows the PCTides forecast track of Isabel using winds and pressures from a) COAMPS, b) NOGAPS c) the observed hurricane track from the National Hurricane Center (NHC) and d) the PCTides forecast (using winds generated from the Holland model) starting from the NHC projected path approximately 24 hours prior to landfall.
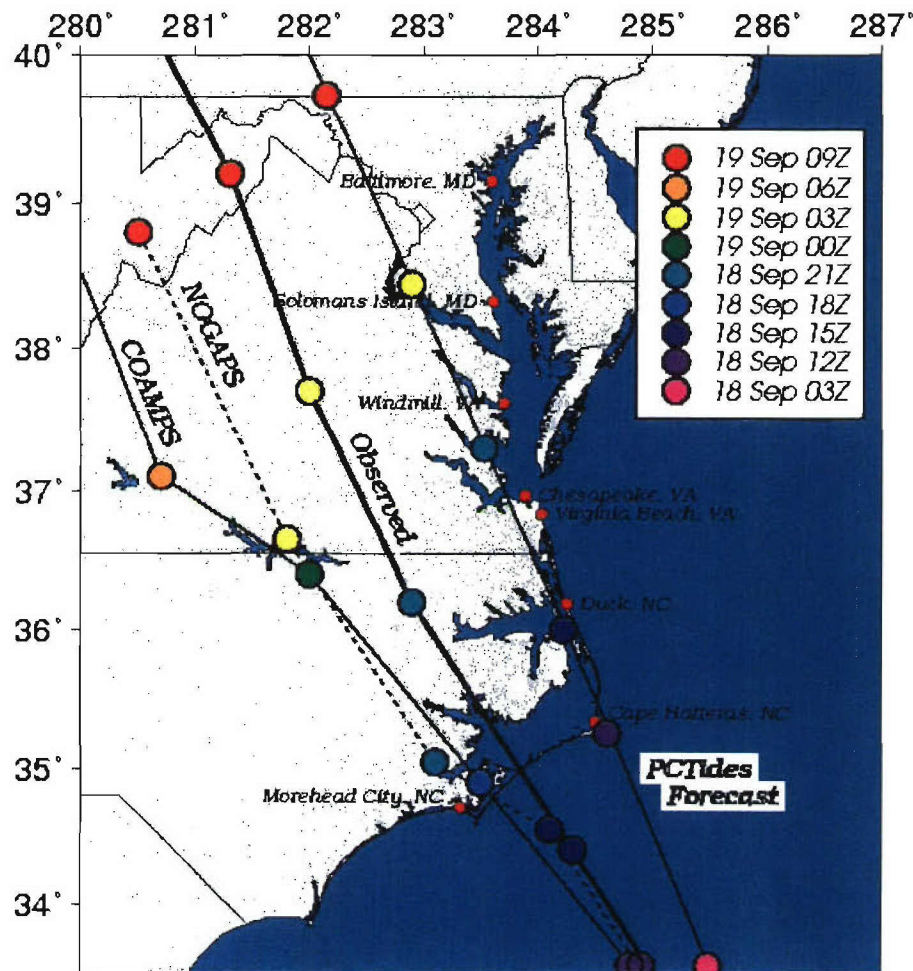

Figure 12. Hurricane Isabel forecast and observed tracks.

Figure 13 represents the PCTides forecasts for the Baltimore station. Seven hurricane driven simulations are shown along with the observations at the station, the IHO data for the station and PCTides driven with no winds, only tidal forcing. The first two panels present the PCTides results using the observed track (hindcast) and the NHC forecast track respectively, as applied to the Holland model. The numbers associated with each

solution indicate the size of the storm defined by the radius of maximum winds (RMW). The third panel is the PCTides result driven by COAMPS and NOGAPS predictions while the final panel is the PCTides tidal prediction only, versus the IHO data. It should be noted that PCTides did include tide (as well as wind and pressure) forcing in each simulation but no data assimilation.
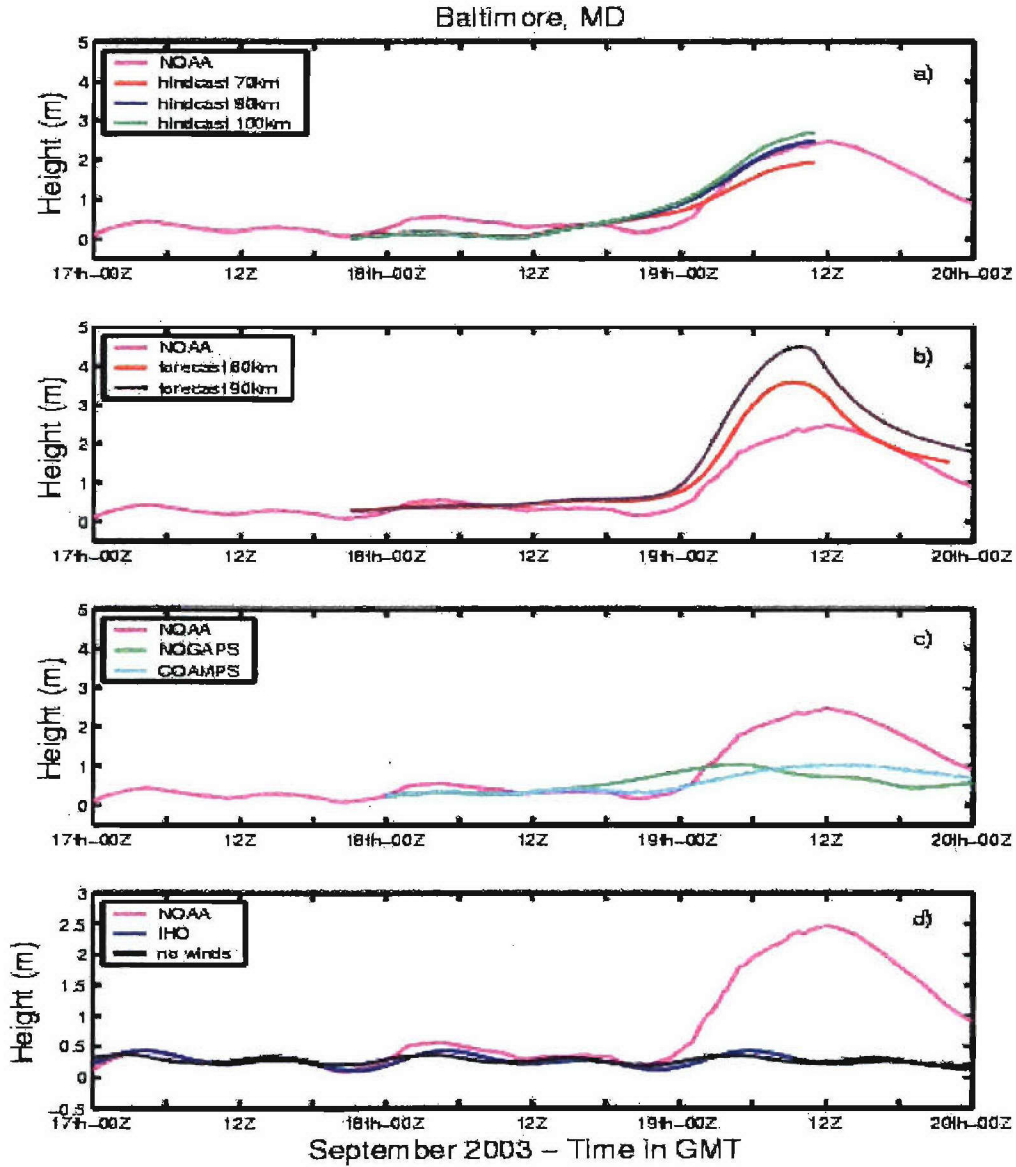

Figure 13. Observed water level above MLLW at the Baltimore, MD station versus water levels driven by a) the Holland model hindcast using 70 km, 90 km and 100 km RMW, b) the Holland model forecasts using 60 km and 90 km RMW, c) NOGAPS and COAMPS forecast and, d) IHO calculated tidal height and PCTides non-wind driven tidal heights for the period from 00Z on September 17th through 00Z on September 20th. NOTE: Figure 13d has a different height scale (-0.5 to 3.0 m) from figure 13 a-c (-0.5 to 5.0 m).

A statistical evaluation of the PCTides results driven by each type of atmospheric forcing is given in Table 6.

| | Amplitude (meters) | | Phase (minutes) | |
	AME	RMS	AME	RMS
COAMPS	.62 (.79)	.76 (.95)	75 (58)	90 (64)
NOGAPS	.72 (.88)	.83 (1.01)	148 (193)	305 (254)
Forecast 60	.52 (.49)	.63 (.68)	90 (128)	121 (120)
Forecast 90	.68 (.84)	.94 (1.18)	168 (100)	170 (100)
Hindcast 70	.45 (.70)	.55 (.61)	134 (68)	182 (69)
Hindcast 90	.25 (.42)	.39 (.60)	112 (68)	51 (69)
Hindcast100	.22 (.43)	.38 (.55)	110 (65)	50 (68)

Table 6. Absolute Mean Error (AME) and Root Mean Squared (RMS) Error associated with the prediction of the amplitude and phase of peak storm surge for each PCTides simulation. Values in parentheses were calculated using the three stations (Beaufort, NC; Chesapeake, VA and Baltimore, MD) which remained uninterrupted throughout the storm.

These results indicated that given the correct path and hurricane definition (100 km RMW), PCTides did a very good job of predicting storm surge with an RMS height error of 38 cm and an RMS phase error of 50 minutes. Note that PCTides driven by COAMPS also did a reasonable job of predicting the phase and amplitude of the surge. Also interesting is the fact that the predicted path provided by the hurricane center approximately 24-hours before landfall was approximately 100 km east of the actual track. This study showed that PCTides could do an accurate job of predicting storm surge and that a useful application of PCTides prior to landfall should include an ensemble of forecasts indicating the range of surge possible for coastal regions.

Recent Uses of PCTides

PCTides was used in the Maritime Rapid Environmental Assessment Trial (MREA04), which took place off the coast of Portugal from March through April 2004 (Figure 14). During this time, PCTides was run using real-time COAMPS wind and surface pressure fields to produce a 48-hour tidal elevation forecast. This forecast was used as input for two wave models also run during the exercise: 1) the NRL Swan wave model (included in the DIOPS system) and 2) the Delft3D model. Figure 15 shows a comparison of tidal elevation from the PCTides forecast and observations from the Sines buoy.
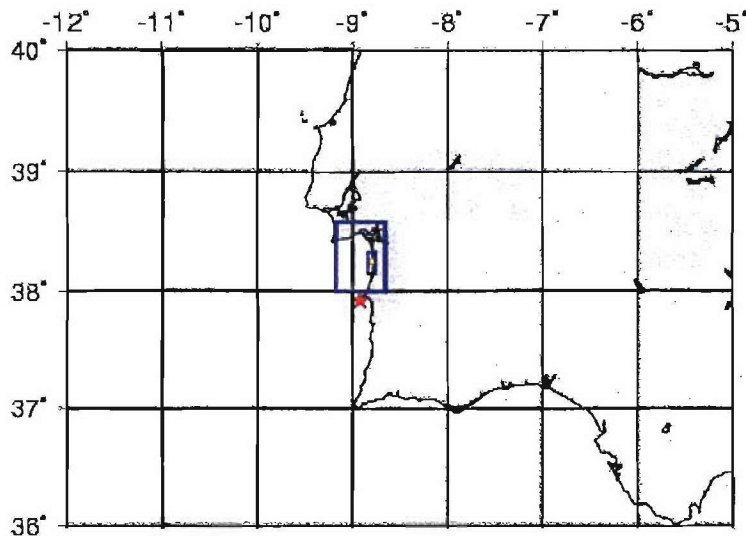

Figure 14. Location of MREA04 exercise off the coast of Portugal. The red star is the location of the Sines buoy. The station Pinhiero da Cruz is located in the smallest box.
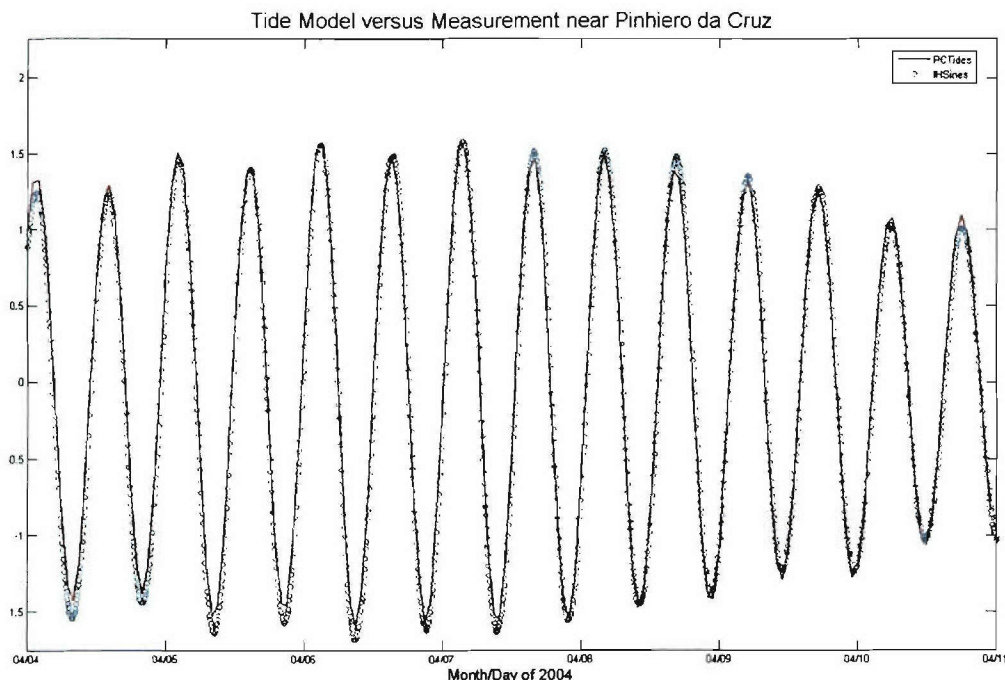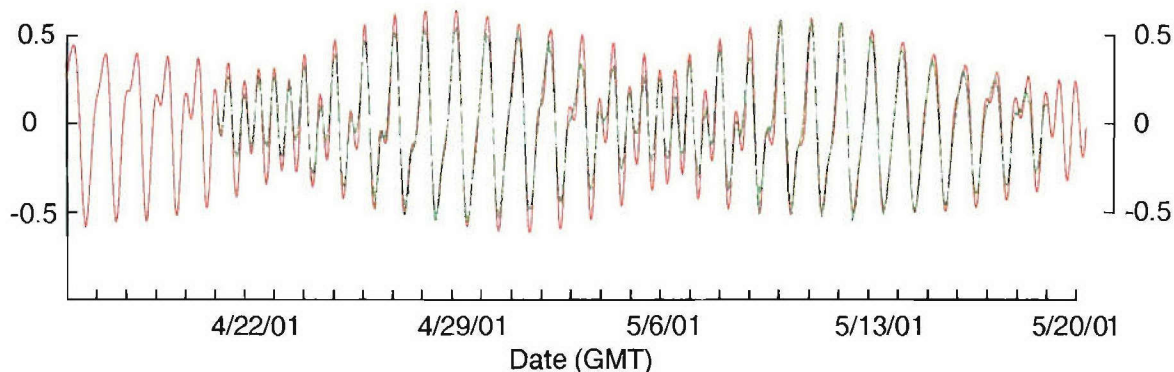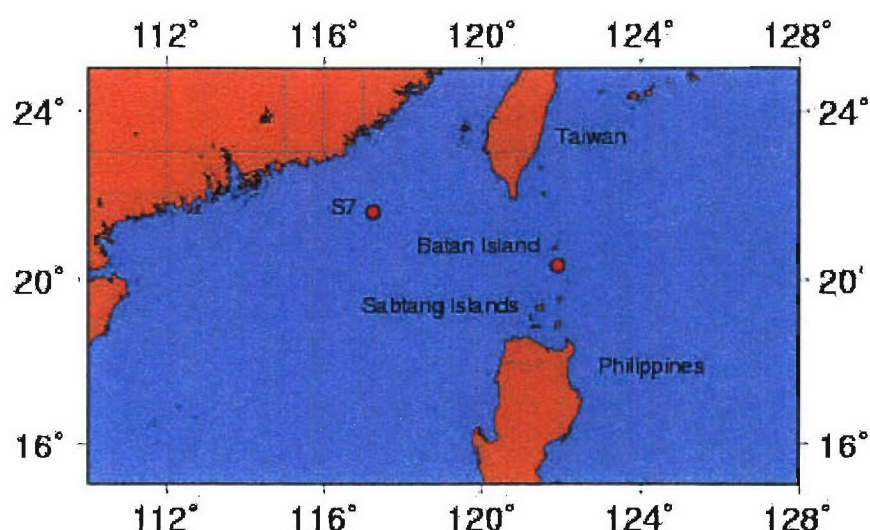

Figure 15. Comparison of tidal elevation from the PCTides forecast (red) and observations from the Sines buoy (green).

During the spring of 2000 and 2001 a major field exercise called the Asian Seas International Acoustics Experiment (ASIAEX) took place in the South and East China Seas (Ramp et al., 2004). PCTides forecasted tidal elevations in the Luzon Strait region (figure 16) from April through May 2001. PCTides elevations were compared to the ASIAEX mooring S7 located along the Chinese continental shelf and resulted in very good agreement (figure 17). The model slightly overestimated the tidal heights with a root mean squared error of 15 cm. During the same time period, PCTides forecasts were compared to observations between the Batan and Sabtang Islands, approximately 500 miles away from mooring S7 (figure 16). As part of this study, PCTides elevations were compared against the Oregon State University (OSU) TOPEX/Poseidon crossover global inverse solution TPX0.3 for the same location. The inputs and methodology of the two models are quite different, however both models produced virtually identical results for locations in the northeastern South China Sea and the Luzon Straits.

Figure 16. Location of ASIAEX mooring S7 and observations between Batan Island and Sabtang Islands (Luzon Strait).

Figure 17. Observed (green) and PCTides generated (red) barotropic tidal elevations (m) at ASIAEX site S7 on the Chinese continental slope.

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During 2004, NRL Code 7440 ran PCTides to correct tidal variation from bathymetry data acquired from the "AQS – 20" mine hunting sonar. This sonar is used to detect, classify and identify moored and bottom mines using side-scan, forward-looking, and volume search sonar from deep to very shallow water. The accuracy of the environmental data collected can be affected by tides in the geographic area of interest. Local tide variations can be provided by the PCTides system for adjusting this bathymetric data. This work was presented at the SPIE Security and Defense Symposium by Costin Barbu and Will Avera (Barbu et al., 2005). This corrected bathymetry could provide a useful tool for Mine Warefare Operations.

Summary

The PCTides system, developed by the Naval Research Laboratory, has been evaluated in a number of different locations by a number of different users. Consensus from these users is that PCTides is a useful and acceptably accurate tool for the prediction of tidal heights and wind driven surge. PCTides 2.0, recently submitted to OAML is an improvement over the previous version in a number of ways including improved databases, user-friendly software and a UNIX-based code.

Acknowledgements

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Appendix A

From: Commanding Officer, U.S. Naval European Meteorology and
         Oceanography Center, Rota, Spain
To: Commander, Naval Meteorology and Oceanography Command,
         Stennis Space Center, MS (Code N531)

Subj: ASSESSMENT OF THE NAVY RELOCATABLE TIDE/SURGE MODELING SYSTEM

1.   The Windows NT version of the Navy Relocatable Tide/Surge Modeling
System (PCTIDES) was installed at the Naval European Meteorology and
Oceanography Center (NEMOC) in January 2000. The following qualitative
feedback, derived from exercise and operational support, is provided:

   a) PCTIDES has the potential to be an excellent tidal modeling system.
      The flexibility of creating user-defined tidal stations and defining
      detailed model parameters greatly enhances our ability to support
      operational customers.

   b) Although atmospheric forcing is integrated into PCTIDES, NEMOC does not
      typically use this capability as most requests for tidal data are
      beyond the prognostic time scale for numerical models.

   c) An assessment of model accuracy was conducted for the Rota, Spain local
      area. The evaluation consisted of designing a 10-km PCTIDES grid and
      comparing model output with historical data ("hindcast") and current
      observations ("forecast"). Our findings were that the model performs
      hindcasts and forecasts extremely well for the local area.

   d) Customer feedback concerning PCTIDES products has been very favorable;
      products are deemed to be valuable in operations and planning.

2.   My point of contact in this matter is LT Gabriel, DSN 727-3967.

                          R. P. GARRETT

Copy to:
Naval Research Laboratory DET, Stennis Space Center, MS

Appendix B

**Proudman
Oceanographic Laboratory**
NATURAL ENVIRONMENT RESEARCH COUNCIL

Dr Bruce Northridge
northridge@cnmoc.navy.mil

7 May 2002

Dear Dr Northridge

PCTIDES

Last year (May 2001) I visited Dr Ruth Preller at NRL Stennis for 2 weeks (sponsored by ONR) as part of an assessment of PCTIDES in European shelf seas. The assessment continued once I had returned to the UK. The objective was to evaluate PCTIDES performance against our own operational storm surge forecasting system which runs routinely (twice-daily) at the UK Met Office. The period April-May 2001 was chosen as the evaluation period.

The NW European shelf is an ideal region to assess the performance of a re-locatable tide-surge modelling system for several reasons: it is a data-rich area with more than 30 tide gauges located around the UK coast; the coast itself is varied, with several estuaries interconnected by open coastal sections; the dynamics of the tides and storm surges differ between the west coast of Britain and the east coast; at POL we have over 30 years experience of modelling and forecasting tides and surges around the UK coast.

Our evaluation took the form of a) designing a PCTIDES grid compatible with our own model grid (approximately 12km resolution) and comparing i) tides and ii) surges during April & May 2001 both with and without PCTIDES assimilation of tidal constants and b) designing and implementing higher resolution PCTIDES grids in specific areas of interest for either tidal characteristics (Bristol Channel has one of the highest tidal ranges in the world) or surge characteristics (Liverpool Bay – direct surge forcing, southern North Sea – external surge forcing).

The overall findings were as follows:

- Tides in PCTIDES on the 12km grid without data assimilation were less accurate than the tuned tides of the POL model
- Tides in PCTIDES on the 12km grid with data assimilation were of similar accuracy to the tuned tides of the POL model
- Surges in PCTIDES on the 12km grid with data assimilation were of similar accuracy to those of the POL model only along open coasts; in the estuaries they were significantly worse
- Surges in PCTIDES on the higher resolution grids with data assimilation were of similar accuracy to those of the POL model

The evaluation has shown that PCTIDES can produce tides and storm surges of comparable quality to those provided by a specifically tuned system. The initial 'first guess' PCTIDES could produce equivalent results only on open coasts, requiring data assimilation of tidal constants to improve on the tidal response in estuarine waters. A noticeable fact was the role the data assimilation played: the data-rich UK coast sometimes over-specified the assimilation, requiring careful consideration when having tide gauge locations in a coarse (12km) adjacent model grid cells. It also showed the value of the data assimilation as without it the results were not as good as in the POL model. Higher resolution models could produce better tide and surge results.

I was impressed with the capability of PCTIDES. Initial results were obtained within hours of setting up the system and comparable results (to a system established over 20 years and continuously monitored) obtained within days. The ease with which higher resolution models could be set up made exploring optimum grid resolutions a simple task, and demonstrated how these could improve results. The role of available tidal data should not be underestimated however, the data-rich NW shelf enabled PCTIDES to perform well in this area.

If you require further details I would be pleased to discuss the results of my evaluation with you at greater length.

Yours sincerely

Roger Proctor

Appendix C

PCTides OPTEST report

1. Purpose and summary

This report summarizes the PCTides operational evaluation plan, implementation of that plan and the results. To maximize relevance to current operations, the evaluation was designed and implemented at NLMOC and NPMOC (San Diego) over 3 months for 12 different stations. In summary, the report recommends that the basic model should be included in OAML and is suitable for fleet use after certain modifications and with caveats for operational use. We recommend the modified version of PCTides be included into the NITES software suite and on in the MET team laptops. The modifications recommended include changes in user interface, product output and display. The caveats recommended are caution in interpretation of model outputs when run near river outflows and for large semi-enclosed bays and estuaries where wind direction seriously affects tidal response. Guidance for these interpretations should be included in the operations manual.

2. Operational Test

The OPTEST was conducted both at NLMOC (Norfolk) and NPMOC (San Diego) between 1 March to 31 June, 2001. The model was run by the Center's operational watch once a day for 90 days making forecasts 12, 24 and 48 hours ahead using in parallel COAMPS and NOGAPS windfield forcing at 12-hour intervals throughout the forecast period.

The numerous widely separated stations tested the model's ability to forecast tidal heights at any required location, a major improvement over GFMPL. The test area's tidal station locations were inserted into PCTides as forecast points. The NOAA tidal station data were QC'd at NOAA and joined with the forecast water levels for statistical analysis. The primary parameters used are

- AMD (meters): Absolute mean difference between forecast and observed water levels
- Phase (minutes): Mean phase difference between forecast and observed times of high and low water.
  Absolute values were not used so that the +/- "lag" effect could be observed. + indicates model lag.
- RMSE (meters): Root mean square error of forecast water levels from observed.
- RMSPH (minutes): Root mean square error of the forecast phase from the observed phase.

Since PCTides current predictions are for barotropic conditions only, current predictions were not validated. It is recommended this output be eliminated because the operator could be misled if such values were relied upon in the common baroclinic situation.

The pass/fail criteria were selected so as to be a significant improvement over the information presently available to the Naval operator.

1.) The root mean square percent error of PCTides predicted water relative to mean sea level (MSL) vs. NOAA observed water levels relative to MSL must be less than 1.2 foot (0.365 meters).

2.) The root mean square percent error of PCTides predicted water levels max/min times vs. NOAA observed water level max/min times must be less than 45 minutes.

3.) Results

Overall, PCTides performed very well, passing 18 of 24 statistical criteria. The six failures were all in phase and all at the same stations. The West Coast stations passed everything.

24 hour forecast results

STATION	AMD (M)	PHASE (MIN)	RMSA (M)	RMSPH (MIN)	RESULT
Baltimore	0.28	-31.6	0.32	59.4	passed amplitude failed phase
Solomon Island	0.10	-40.8	0.14	53.8	passed amplitude failed phase
Windmill Point	0.08	68.6	0.11	69.2	passed amplitude failed phase
Sewells Point	0.09	20.1	0.12	20.8	Passed both
Chesapeake B/T	0.09	-12.4	0.12	23.7	Passed both

Kiptopeke	0.09	-5.9	0.12	18.2	Passed both
Lewes, Del.	0.21	2.4	0.24	14.4	Passed both
Duck, N.C	0.10	-9.8	0.13	20.5	Passed both
Port Angeles	0.25	-7.73	0.32	25.52	Passed both
Seattle, Wash.	0.15	-29.83	0.18	31.09	Passed both
Kodiak, Alaska	0.22	26.05	0.26	32.62	Passed both
Southern Calif.	0.10	0.65	0.12	24.28	Passed both

24 - 48 hour forecast results

STATION	AMD (M)	PHASE (MIN)	RMSA (M)	RMSPH (MIN)	RESULT
Baltimore	0.27	-46.3	0.32	62.1	passed amplitude failed phase
Solomon Island	0.10	-51.3	0.14	56.4	passed amplitude failed phase
Windmill Point	0.08	57.5	0.11	70.4	passed amplitude failed phase
Sewells Point	0.10	8.8	0.13	21.0	Passed both
Chesapeake B/T	0.09	-22.1	0.11	23.2	Passed both
Kiptopeke	0.09	-16.8	0.12	18.0	Passed both
Lewes, Del.	0.21	-8.6	0.24	14.8	Passed both
Duck, N.C	0.10	-18.3	0.13	20.0	Passed both
Port Angeles	0.25	-12.69	0.32	26.25	Passed both
Seattle, Wash.	0.15	-33.18	0.18	30.51	Passed both
Kodiak, Alaska	0.22	21.92	0.27	33.04	Passed both
Southern Calif.	0.10	-2.05	0.13	27.82	Passed both

The forecasts exceeding the threshold can be explained as follows:

Baltimore and Solomon Island: as harbors sitting at the end of a long SE fetch, an unusual sensitivity to forecast wind direction is evident in the data. Since this geographical situation is not uncommon, a caveat is indicated warning the user to interpret the PCTides forecast in light of this local sensitivity to wind direction.

Windmill Point: tidal measurement station is located inside a river mouth. Since PCTides does not include river outflow, the forecasts would have the added error during rain events

Although the following stations passed the criteria, the optest revealed other errors and sensitivities. At Kodiak, Alaska, the station location was incorrectly inserted into PCTides, causing the forecast to be made for a location in 85 m. (285 ft.) of water. At the Southern California station, phase error was shown as a partial function of the grid scale chosen. For this station, NRL suggested a grid resolution below 10 km. However, the operator chose 17 km. and produced a phase error of 24 minutes. Later runs at 5 km. grid showed a 5 minute phase error. This phase error source was also a factor at Kodiak, Alaska. Therefore, a caveat should be included warning the user to use a grid resolution <10 km.

The OPTEST also revealed problems with the user interface, product dissemination and identification of area of interest. Though feedback from various users at both NPMOC and NLMOC, potential improvements were noted and are listed in the recommendation section below. Since PCTides code was written to run both on DOS and UNIX, we suggest that flexibility be retained and the existing user interface modified accordingly.

7. Recommendation

This panel finds the relocatability of PCTides is a significant improvement over GFMPL. PCTides eliminates the need for the operator to estimate what the water height at anchorage will be some lateral distance from the GFMPL data station location, a considerable source of error. While we have concerns regarding sensitivity of wind direction, this can

be addressed by a caveat. The user interface should be improved for inclusion in the NITES software suite before PCTides becomes operational.

We therefore recommend that PCTides is suitable for fleet use and inclusion in the NITES software suite only after the following improvements have been made.

Installation: The program must be configured such that installation from a CD or diskette by an untrained user is simple and effective.

User interface:

    a.) The DOS windows functions should be incorporated into the existing code for windows and formatted for inclusion in the NITES software suite.

    b.) The batch files of the wind forcing be a default chosen initially by the user so as to retain the options of choosing a selected model or point source winds and to minimize the keystrokes required to run the model

    c.) Graphics should be modernized. The displayed coastlines should represent the chosen grid resolutions. During setup, the program should allow insertion of wind file location in the local LAN. This should be a default so the user need not re-enter it each run.

    d.) The source of the wind forcing used should be on the screen and saved in the product files.

    e.) Defining a grid should be made similar to Metcast Client. The user should be able to rubber band an forecast area and identify the tidal stations by enter lat/lon. The program should invisibly call the appropriate tidal data, bathymetry and wind field.

    f.) Grid resolutions should be in kilometers.

    g.) A pop-up window warning should be included that tells the user the depths of all chosen stations and when any selected point is on land or has a depth beyond a practical threshold level.

Products:

    a.) Output of prediction curves should be user choice formats (tif, gif, etc) compatible with JMV.

    b.) An option for automatically emailing the output to a user-defined list of addresses should be included..

    c.) Display of barotropic currents should be eliminated to avoid operational use in baroclinic waters.

    d.) Auto-insertion into designated web pages should be built in for use at Navy Centers. The web addresses and other info can be inserted first time by the user

Caveats:

    a.) The user should be warned against using the model in or near river mouths. Guidance should be given on the best interpretation of model output.

    b.) If the forecast position is inside semi-enclosed waters, the user should be warned about forecast sensitivity to winds in directions parallel to the bay's major axis. Some guidance for this interpretation should be written and included to help the user estimate the phase and amplitude depending on wind vector forecasts.

    c.) A general guide of accuracy in water height and timing based on OPEVAL data should be included.

If the above modifications are made satisfactorily, this committee will approve PCTides for operational use.

Cordially,

                                     29 January, 2002

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Dr. Walt McKeown   STO, NLMOC (Chair)

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Kim Curry   STO, NPMOC, San Diego

_____

Dr. Ruth Preller   Developing scientist, NRL

Appendix D

The Operational Evaluation of the Navy's Globally Relocatable Tide Model (PCTides)

R.H. Preller, P.G. Posey and G.M. Dawson, NRL

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Abstract - The U.S. Naval Research Laboratory has developed a globally relocatable tide/surge forecast system. This system runs on a UNIX platform but was designed originally for PC-based use and is referred to as PCTides. The core of the system is a 2-dimensional barotropic ocean model. The model is forced with boundary conditions from a global tide model and uses surface winds and pressures (if available) and/or astronomical forcing. The global ocean bathymetry is a 2-minute global database developed by the Naval Research Laboratory. Atmospheric forcing from the Navy's global or regional models is provided through the METCAST system and used to generate real time, wind driven forecasts. PCTides output includes time series of tidal height deviations at each grid point of the model and time series of tidal height deviations at higher frequency (usually 10-12 minutes) at specified point locations. Barotropic tidal currents are also produced by the system.

PCTides has successfully completed its operational evaluation performed by the Naval operational centers located in Norfolk, Virginia and San Diego, California. PCTides was run daily in real time to forecast tidal height deviations from regions along the east and west coasts of the United States. The model forecasts were compared to real time observations from the National Oceanic and Atmospheric Administration (NOAA) coastal tide gauges. Results from these evaluations showed an average amplitude error of 15 cm and a phase error of 30 minutes. Specific examples of PCTides hindcasts and forecasts for various areas will be presented and discussed.

I. INTRODUCTION

Over the past 3 years, the Naval Research Laboratory (NRL) has developed a globally relocatable tidal prediction capability that can run on either a PC or UNIX based system. This prediction system, call PCTides, has a 2-dimensional (2-D) barotropic ocean model as its core (Fig.1). PCTides uses this depth-integrated shallow water model to predict both the barotropic currents and sea level heights on or near continental shelves [1,2]. It contains a

wetting and drying algorithm for the simulation of coastal flooding due to tides and/or storm surge. Surface winds, pressure and/or astronomical forcing drive this model. A global tide model, the Finite Element Solutions 95.1/2.1 (FES95.1/2.1) is used to provide tidal conditions at the open boundaries of the ocean model [3].
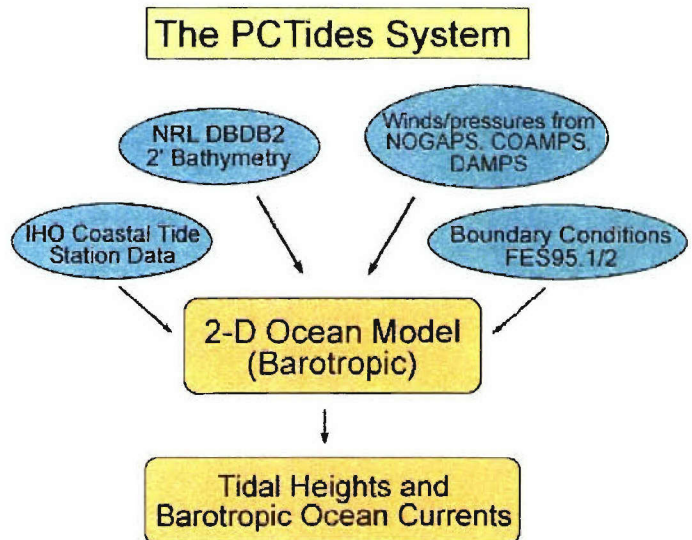

Fig.1. Schematic of the PCTides system.

All databases, except for the wind forcing, are internal to the PCTides system. These include: 1) bathymetry, a 2-minute global data base derived from a combination of the Navy's DBDBV data, the Smith and Sandwell dataset, the DAMEE North Atlantic data, the IBCAO Arctic data, as well as regional data sets from the Gulf of Mexico and Yellow Sea 2) the FES95.1/2.1 solutions and 3) tidal station data from the International Hydrographic Office (IHO) database. The IHO data is used for either model validation or for data assimilation.

In most applications of the system, winds from the Navy Operational Global Atmospheric Prediction System (NOGAPS) model [4], the Coupled Oceanographic and Atmospheric Mesoscale Prediction System (COAMPS) or

the Distributed Atmospheric Prediction System (DAMPS) are available and therefore used. These fields are used daily at the operational centers and retrieved typically through the Navy's METCAST system.

Tidal heights and barotropic ocean currents are the products of the PCTides system. The user has the option of pre-selecting station locations where high frequency (10-12 minute) tidal time series forecasts are produced. Stations are identified by latitude and longitude locations prior to the forecast. These time series are written to a file containing station information, date, time, tidal elevation, current speed and direction. The forecast may be viewed as a printed text file or plotted as a time series curve. In addition to the station forecasts, tidal elevations and currents are output at each model grid point at a pre-selected time interval with a minimum value of 30 minutes.

During the development and testing of PCTides, the system was evaluated against observations in several locations. Tidal height data was available for comparison in most of these locations. In a few select regions (Yellow Sea and Korea Strait), tidal current information was also available. The evaluation of PCTides forecasts to these observations gave us confidence in the product. In addition, PCTides was "beta-tested" at the Navy's operational center in Rota, Spain. Positive comments from the beta-test users, as well as the acceptable results from the model comparisons to the observations, allowed us to proceed to the next step, the operational evaluation of the model called the OPTEST.

From March through June 2001, the Naval Atlantic Meteorology and Oceanography Center (NLMOC) at Norfolk, Virginia conducted the operational evaluation of PCTides. A 48-hour forecast was generated each day using wind and surface pressure forcing from NOGAPS. The resultant tidal height fields from the model were evaluated against observations at selected points along the eastern coast of the United States.

During the same time period, the Naval Pacific Meteorology and Oceanography Center (NPMOC) at San Diego, California conducted an additional operational evaluation of PCTides. Again a 48-hour forecast was generated each day using wind and surface pressure forcing from NOGAPS/COAMPS. As before, the resultant tidal height fields from the model were evaluated against observations at select points along the western coast of the United States.

II. DISCUSSION

The evaluation of the PCTides forecast was performed by comparing the 48-hour model forecasts to the corresponding real time observations of the Mean Lower Low Water (MLLW) available from the NOAA website [5] at the pre-determined coastal stations. The NOAA observations were run through a 1-2-1 Hanning smoother several times to remove high frequency variability. Since tide models produce the tidal variation about the mean

water level, an important aspect of this evaluation was an appropriate way to remove the mean from the observations. Although NOAA has a 19-year observational mean for each of the pre-determined stations, such a mean would probably not be available at every point of interest to the Navy. Therefore both centers approached the issue of removing the mean in the following way. A 2-day mean was computed from the data for every 48-hour period associated with the 48 hour forecast. The mean was then subtracted from the raw observations therefore removing the MLLW and resulting in a more realistic comparison between model amplitudes and observations.

At the end of the evaluation period, the model output was quantitatively compared to the NOAA observations. Statistics were calculated for each station's 0-24 hour forecast and 24-48 hour forecast over the entire OPTEST period by comparing model versus observed minimum and maximum tidal elevations. The following statistics were studied:

- AME - Absolute Mean Error of amplitude (meters)
- RMSA -Root Mean Square Error of amplitude (meters)
- MPD - Mean Phase Difference (minutes)
- RMSP - Root Mean Square Error of phase (minutes)

The pass/fail criteria were determined prior to the OPTEST evaluation period. The root mean square amplitude error of PCTides tidal elevation forecast vs. NOAA observed tidal elevation had to be less than 1.2 feet (0.365 meters). The root mean square phase error of PCTides peak tidal times versus NOAA's peak observation times must be less than 45 minutes.

NRL developed a website during the OPTEST where the model forecasts were displayed and compared to the NOAA observations. Each day's 48-hour forecast was displayed along with a plot of the 48-hour forecast from two days earlier with the NOAA observations overlaid. This allowed the OPTEST scientists to view the model/data comparison and develop confidence in the product.

A. U.S. East Coast evaluation

The U.S. East Coast evaluation focused on the Chesapeake Bay area (Fig. 2). A model domain was set up to cover this region using a grid resolution of 4.4 km and 68 x 141 grid points. A total of 8 stations were chosen and then compared to NOAA tidal observations during the same time period. The coastal stations included in the comparison were: Baltimore (39.15° N, 76.40° W), Solomon Island (38.32° N, 76.39° W), Windmill Point (37.62° N, 76.30° W), Sewell's Point (36.95° N, 76.33° W), Chesapeake (36.97° N, 76.11° W), Kiptopeke (37.17°

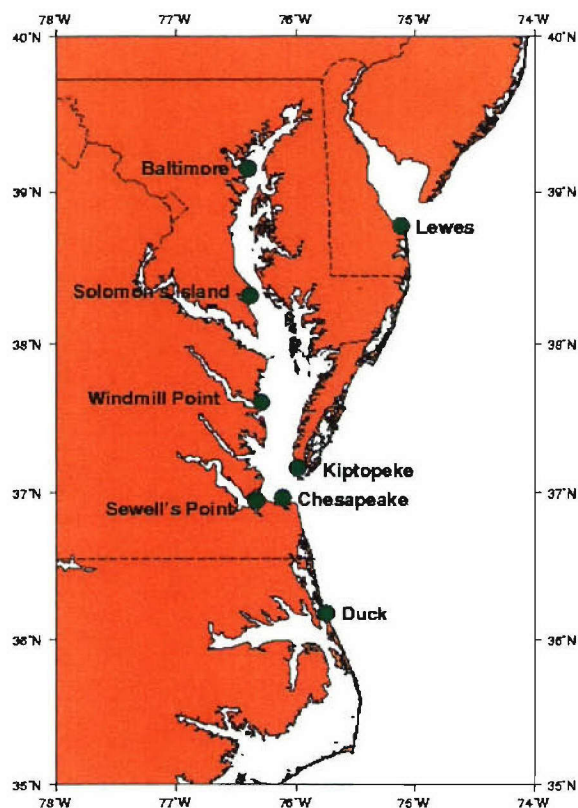N, 75.99° W), Lewes (38.78° N, 75.12° W), and Duck (36.18° N, 75.75° W).

Fig. 2. Chesapeake model domain with NOAA observational stations indicated.

PCTides forecasts were run each day on a 1 GHz, Pentium III, Windows NT desktop PC. The model was cold-started each day and run for a 24-hour hindcast (with atmospheric forcing) and then continued the 48-hour forecast. Tests made prior to the operational evaluation determined that the 24-hour hindcast was the optimal spin up time for a typical PCTides forecast region. The model run time including the retrieval of atmospheric forcing took approximately 10 minutes. Figure 3 is an example of the forecast of tidal elevation from the OPTEST at the Chesapeake station.

PCTides (Black) vs NOAA Observations (Red)
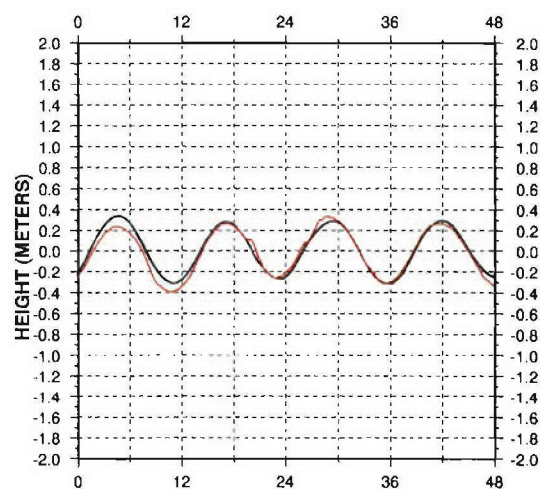
Fig. 3. 48-hour tidal height (meters) from PCTides (black line) vs NOAA Observation (red line) at the Chesapeake station (see Fig. 2). Plot valid for July 11, 2001 at 00Z.

Table 1 contains the statistics for all eight stations during the first 24 hours of each daily forecast. There were 3 stations that passed the amplitude criteria but failed the phase criteria (see highlighted columns on Table 1). The 3 stations that failed the criteria were Baltimore, Solomon Island and Windmill Point. In general, predictions for stations along the outer coast are more accurate than those stations located farther inland within the bay/estuary. The inland stations are more susceptible to the effects of wind and other meteorological effects than stations along the outer coast. Baltimore and Solomon Island stations are located in harbors sitting at the end of a long south-eastern fetch and therefore are extremely difficult to forecast correctly. Winds that blow along the length of the bay have been known to cause water levels to be 1-2 feet above or below the predicted tides. The NOAA Windmill station was positioned inside a river mouth. PCTides does not include river outflow, which could have added error during strong outflow events.

Table 1. First 24 hour forecast comparison
PCTides vs NOAA Observation Stations

Station	AME (m)	MPD (min)	RMSA (m)	RMSP (min)
Baltimore	0.28	-31.6	0.32	59.4
Solomon Island	0.10	-40.8	0.14	53.8
Windmill Point	0.08	68.6	0.11	69.2
Sewell's Point	0.09	20.1	0.12	20.8
Chesapeake	0.09	-12.4	0.12	23.7
Kiptopeke	0.09	-5.9	0.12	18.2
Lewes	0.21	2.4	0.24	14.4
Duck	0.10	-9.8	0.13	20.5

The mean phase difference (MPD) was calculated by subtracting the NOAA observation station data from the PCTides model forecast. Therefore a positive bias means that the model high or low tidal peak occurred after the observed NOAA peak. In six out of the eight pre-selected stations, the model's RMS amplitude error varied from the NOAA observations by less than 15 cm/sec. The other two station's RMS amplitude error varied less than 35 cm/sec. Five out of the eight modeled stations had RMS phase errors that varied less than 24 minutes when compared to the NOAA observations. The second 24-hour forecast period comparison was generally the same as the first 24-hour period and therefore will not be shown. Overall, PCTides performed very well, passing both phase and amplitude criteria in 5 out of the 8 stations for both the first and second 24-hour period comparison.

B. U.S. West Coast evaluation

Three regions were chosen for evaluation along the US West Coast: the southern California Coast, the southern coast of Alaska, and the Washington State/British Columbia waterways. The first domain, the southern California coast (Fig. 4), used a grid resolution of 17 km and 124 x 98 grid points. Only one station in this area was chosen and then compared to the NOAA tidal observation during the same time period. The station was located at the Scripps Institute pier (32.87° N, 117.27° W).
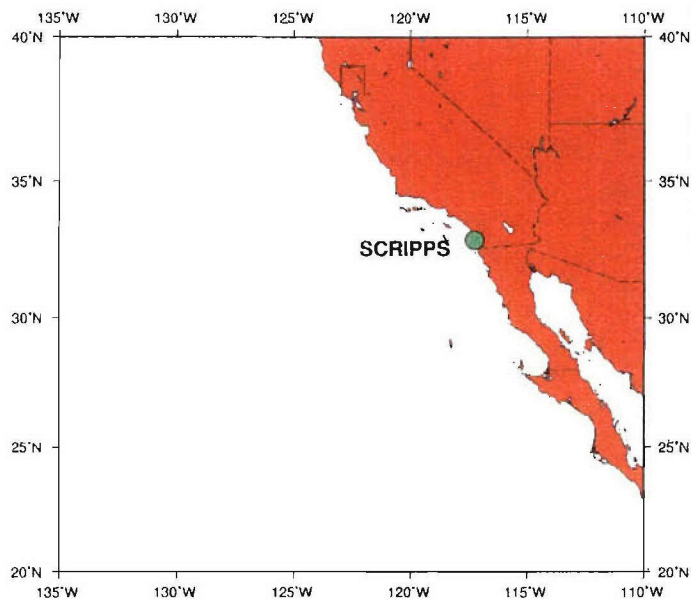

Fig. 4. Southern California model domain with the NOAA observational station indicated.

As in the east coast evaluation, the west coast evaluation was run each day on a 1 GHz, Pentium III, Windows NT desktop PC. Each of the three models was cold-started each day and run for a 24-hour hindcast (with atmospheric forcing) and then continued the 48-hour forecast. All three west coast evaluation regions were run using this spin-up

method. The total model run time for the three areas, using either COAMPS (Southern California and Puget Sound area) or NOGAPS (Kodiak Island area) atmospheric forcing, took approximately 30 minutes. This 30 minute time frame also included the retrieval and processing of the atmospheric forcing. Figure 5 is an example of the forecast of tidal elevation from the OPTEST at the SCRIPPS station location.

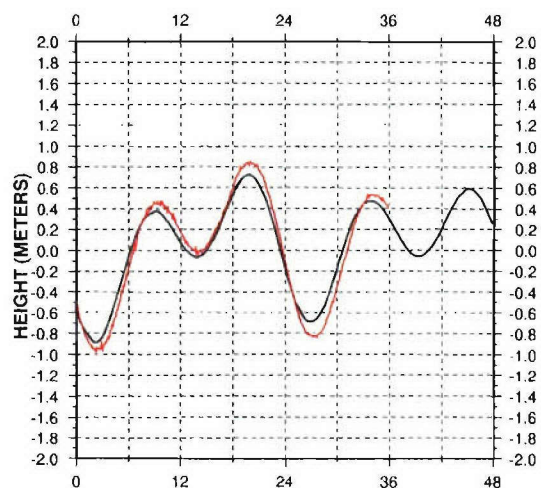### PCTides (Black) vs NOAA Observations (Red)

Fig. 5. 48-hour tidal height (meters) from PCTides (black line) vs NOAA Observation (red line) at the Scripps station (see Fig. 4). Plot valid for June 25, 2001 at 12Z.

The second domain covered the southern Alaska coast including Kodiak Island (Fig. 6). The grid resolution was 25.1 km and 117 x 79 grid points. Only one station was chosen and compared to the NOAA tidal observations. The station was located on Kodiak Island (57.71° N, 151.90° W).
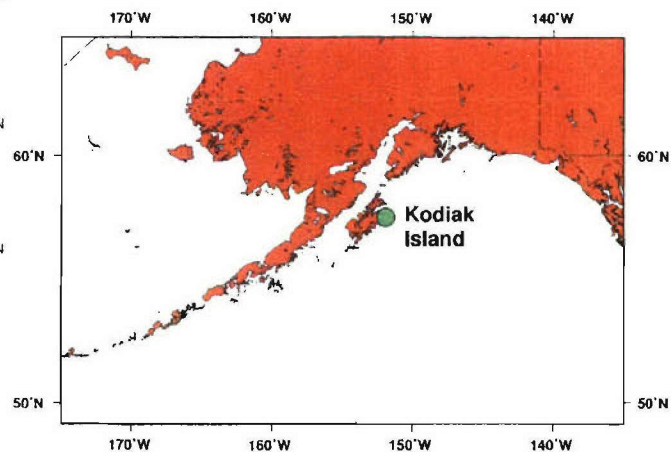

Fig. 6. Kodiak Island model domain with the NOAA observational station indicated.

The third domain covered the Strait of Georgia, the Strait of Juan DeFuca and the Puget Sound (Washington State) area (Fig. 7). The grid resolution was 2.7 km and 132 x 182 grid points. Two stations were chosen and then compared to NOAA tidal observations. The coastal stations included in the comparison were: Port Angeles (48.19° N, 123.43° W) and Seattle (47.55° N, 122.41° W).
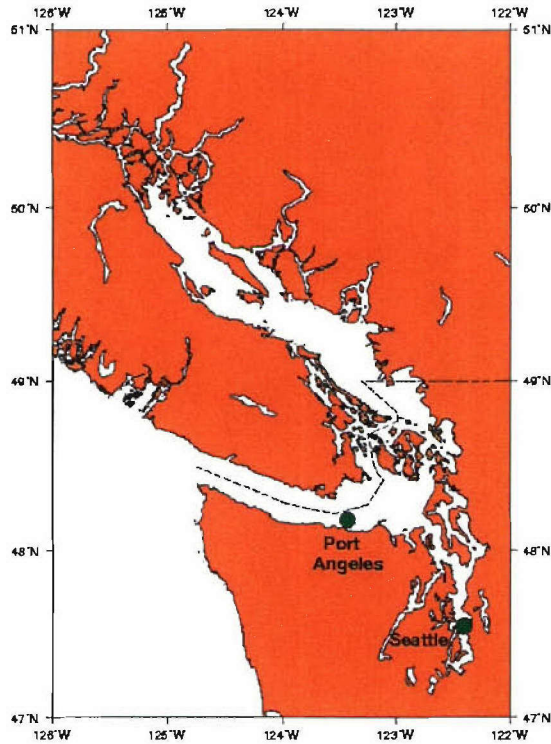

Fig. 7. Puget Sound (Washington State area) model domain with the NOAA observational stations indicated.

Table 2 contains the statistics for the four stations included as part of the west coast evaluation test during the first 24-hours of each daily forecast.

Table 2. First 24 hour forecast comparison
PCTides vs NOAA Observation Stations

Station	AME (m)	MPD (min)	RMSA (m)	RMSP (min)
Scripps	0.10	0.65	0.12	24.28
Kodiak Island	0.22	26.05	0.26	32.62
Port Angeles	0.25	-7.73	0.32	25.52
Seattle	0.15	-29.83	0.18	31.09

During the evaluation along the western coast of the United States, all four stations passed the criteria for both amplitude and phase. The modeled RMS amplitude error of all four stations varied less than approximately 35 cm/sec. The modeled RMS phase error of all four stations varied less than 35 minutes from the NOAA observations. Although all stations passed the criteria, the evaluation revealed several sensitivities of the PCTides model. At the Kodiak Island station, the location was incorrectly inserted into PCTides, causing the forecast to be made for a location in 85 meters of water instead of one closer to the shore (the location of the NOAA observation). The location of the station must be carefully chosen and correctly entered into the model.

At the Scripps station, phase error was shown to be a function of the model's grid size. Typically grids used by PCTides should have a grid resolution of less than 10 km. In the southern California case, the operator chose a grid resolution of 17 km resulting in a phase error of 24 minutes. When a 5 km resolution grid was used over the same area, phase errors were only 5 minutes. The higher resolution grid allowed for better resolution of the bathymetry and coastline resulting in greater forecast accuracy. This grid resolution issue was also a factor at the Kodiak Island station. In that case, the grid resolution was coarse (25.1 km) and did not allow for accurate resolution of the bathymetry or accurate placement of the station. With this in mind, the user needs to create grids with resolution less than 10 km.

The second 24-hour forecast period comparison was generally the same as the first 24-hour period and therefore will not be shown. Overall, PCTides performed very well, passing the OPTEST criteria at all four stations for both the first and second 24-hour period comparison.

C. Improvements

Upon completion of the operational evaluation, each of the centers had an opportunity to make suggestions for system improvement based on their experience running the PCTides system. As a result of these comments, several changes were implemented in the final version of PCTides that was ultimately delivered to the Naval Oceanographic Office. A major concern of the operational centers was that PCTides did not have a convenient method of saving the model output plots to a file that could be easily distributed to the fleet users. Because of this, PCTides graphics were upgraded to save the model output in "gif" format, which can be posted to the center's website for distribution among users. Along with the ability to archive/save plots, the model output graphic package was upgraded to improve the general appearance of the plots.

During the past year, NRL developed a 2-minute global bathymetry data set (NRL DBDB2) based on the Navy's DBDBV data, the Smith and Sandwell dataset, the DAMEE North Atlantic data, the IBCAO Arctic data as well as regional data sets from the Gulf of Mexico and Yellow Sea. A major goal of this new database was to

improve the coastline and island representation and to improve coastline-bathymetry matching. The bathymetry used in the PCTides OPTEST was a 3-minute interpolated dataset based only on DBDBV 5-minute data and its available higher resolution bathymetry data. Comparisons of the 2-minute and 3-minute global data showed greater accuracy in the 2-minute data, particularly along coastlines and in shallow water. Therefore, PCTides was delivered using the new NRL DBDB2 bathymetry dataset.

Another modification to PCTides, suggested during the evaluation, added the capability for the user to input and use a high-resolution bathymetry dataset. This software has been added to the system as an option that is run outside of the PCTides main menu.

The following upgrade to PCTides was also a direct result of user input. Based on the fact that the model grid produces a rectangular grid estimation or representation of the coastline, station locations that are very near the coastline may fall on land. PCTides now includes an automated process that moves such a station to the nearest ocean (water) point that exists on the model grid and informs the user of this change before proceeding with the forecast.

III. CONCLUSION

Over the past 3 years, the Naval Research Laboratory (NRL) has developed a globally relocatable tidal prediction capability that can run on either a PC or UNIX based system. This prediction system, called PCTides, consist of a 2-dimensional barotropic ocean model driven by a combination of wind and atmospheric pressure fields and/or astronomical forcing. From March through June of 2001, the Navy operational centers at Norfolk, Virginia and San Diego, California conducted an operational evaluation of PCTides. The model made a 48-hour forecast each day including wind and surface pressure forcing from NOGAPS or COAMPS. The resultant tidal height fields from the model were evaluated against observations at selected points along the eastern and western coasts of the United States. In order to pass the evaluation, PCTides had to produce: 1) tidal heights that were less than 1.2 feet (0.365 meters) of the observed data and 2) tidal phases that were less than 45 minutes of the observed data. Overall, PCTides performed very well, as demonstrated in the evaluation, in which 18 out of the 24 statistical criteria were met. During July 2002, PCTides was delivered to the Systems Integration Division at the Naval Oceanographic Office, Stennis Space Center, Mississippi for the Navy's use as a relocatable tidal model.

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